

**BELLCOMM, INC.**

955 L'ENFANT PLAZA NORTH, S.W.

WASHINGTON, D. C. 20024

**SUBJECT:** Reentry Simulation Comparison  
Case 310**DATE:** January 28, 1969**FROM:** I. Bogner  
S. B. Watson

TM-69-2014-1

TECHNICAL MEMORANDUM1. Introduction

Data are presented comparing two Bellcomm entry simulations with simulations developed by three other organizations. The data presented, based upon Apollo Mission C-Prime entries, involve seven check simulations designed to point up simulation differences. The simulations are identified as follows:

- A. NR - North American Rockwell Simulation.
- B. MPAD - Mission Planning and Analysis Division Simulation, Flight Crew Operations Directorate, MSC.
- C. AGCES - Apollo Guidance and Control Evaluation Simulation, Engineering and Development Directorate, MSC.
- D. BC/HES - Bellcomm Hybrid Entry Simulation.
- E. BC/DES - Bellcomm Digital Entry Simulation.

A comparison of the NR, MPAD and AGCES simulations was published by NASA<sup>(1)</sup>. Information from that work appears in the text and appendix of this memorandum.

2. Description of Simulations

## 2.1 NR

The NR reentry simulation is an all digital four-degree-of-freedom (3 translation and one rotation) simulation. Aerodynamic coefficients do not vary with Mach number. The earth model is a rotating Fischer Ellipsoid, and the 1962 Standard Atmosphere is utilized. L/D is varied by changing aerodynamic coefficients.

(NASA-CR-103928) REENTRY SIMULATION  
COMPARISON (Bellcomm, Inc.) 35 p

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## 2.2 MPAD

The MPAD reentry simulation is an all digital four-degree-of-freedom (3 translation and one rotation) simulation. Aerodynamic coefficients vary with Mach number as well as angle of attack. The earth model is a rotating Fischer ellipsoid, and the 1962 U.S. Standard Atmosphere is utilized. L/D is varied by changing the aerodynamic coefficients table.

## 2.3 AGCES

The AGCES utilizes a hybrid computer complex to solve the equations of motion in real time for a fixed-base hardware CM cockpit simulation and a functional mechanization of the SCS. The spacecraft equations of motion contain six degrees of freedom. The earth model is a rotating Fischer ellipsoid, and the 1962 U.S. Standard Atmosphere is utilized. Aerodynamic coefficients vary only with angle of attack. L/D is varied by changing the location of the spacecraft center of gravity.

## 2.4 BC/HES

The BC/HES utilizes a hybrid computer. The equations of motion, which contain six degrees of freedom, are solved in real time. The simulation includes a fixed base CM cockpit mockup with displays and controls necessary to fly manual - SCS entries. The simulation is also capable of flying a completely automatic entry using the Apollo entry guidance and the entry digital autopilot. The earth model is a rotating sphere and the 1962 U.S. Standard Atmosphere is used. Aerodynamic coefficients vary only with angle of attack. L/D is varied by changing the location of the spacecraft center of gravity.

## 2.5 BC/DES

The BC/DES is a digital four-degree-of-freedom (three translation and one rotation) simulation. Aerodynamic coefficients can vary with Mach number and the vehicle is assumed to be always in trim. For purposes of this study aerodynamics are held fixed at the values corresponding to the hypersonic Mach number range. The earth model can be a rotating Fischer ellipsoid but for purposes of this study is made a

rotating sphere. The 1962 Standard Atmosphere is used. L/D is varied by changing aerodynamic coefficients.

### 3. Description of Test Runs

A summary of parameters used for the check cases is included as Table I. The initial conditions for all seven cases were:

Altitude: 400,000 ft.

Inertial Azimuth Angle: 79.469415 deg.

Longitude: -97.84098 deg.

Geocentric Latitude: 31.185049 deg.

Inertial Velocity: as noted in Table I.

Inertial Flight Path Angle: as noted in Table I.

All quantities except those above and those noted in Table I were nominal for Apollo Mission C or C-Prime.

All simulation runs for the NR, MPAD, AGCES and BC/DES simulations were terminated at the nearest data point to 100,000 feet altitude to facilitate comparison with data from AGCES, which is terminated at this altitude due to limitations of the one-dimensional aerodynamic coefficient table.

All BC/HES simulations were started at a state vector corresponding to the 0.05 G state as generated by the BC/DES. For purposes of improved accuracy, computer scaling in the BC/HES does not permit aerodynamic decelerations greater than 12 g. In those cases where, due to high g, the HES terminates prior to 100,000 feet, termination data is compared to the BC/DES.

### 4. Data Presentation

Time histories of key variables for the NR, MPAD and AGCES simulations, as taken from Reference 1, less the data points, are presented as Figures 1 through 26. More than one curve appears on a graph when the time histories of the NR, MPAD and AGCES simulations differ sufficiently to warrant separate curves. With very few exceptions, and within plotting accuracy, all NR, MPAD and AGCES data points fall on the curves. BC/DES and BC/HES time history data points appear on these figures. The time histories include altitude, altitude rate (for non-spinning entries), dynamic pressure and inertial velocity for the seven check cases.

TABLE I - CHECK CASE PARAMETERS

| CASE | $V_1$ , ft/sec | $\gamma$ , deg. | L/D  | Weight, lb. | Atmos.                 | Flight Mode     | Objectives                                      |
|------|----------------|-----------------|------|-------------|------------------------|-----------------|---|
| 1    | 25,700.        | -1.6            | .28  | 13068.      | 62 STD                 | Rolling 20°/sec | Check aerodynamics and S/C rotational dynamics. |
| 2    | 25,700.        | -1.6            | .28  | 13068.      | 62 STD                 | Lift 90°        | Check out-of-plane calculations.                |
| 3    | 25,700.        | -1.6            | .28  | 13068.      | 62 STD                 | Lift up         | Check L/D & aerodynamics.                       |
| 4    | 25,700.        | -1.6            | .348 | 13068.      | 62 STD                 | Lift up         | Check L/D variation.                            |
| 5    | 25,700.        | -1.6            | .28  | 11000.      | 62 STD                 | Lift up         | Check inertia variation.                        |
| 6    | 25,700.        | -1.6            | .28  | 13068.      | +3 $\sigma$<br>(30° N) | Lift up         | Check atmosphere deviation.                     |
| 7    | 36,100.        | -6.4            | .28  | 13068.      | 62 STD                 | Rolling 20°/sec | Check at super-circular velocity.               |

A summary of termination data - altitude, time, relative velocity, latitude and longitude - is presented in Table II. The NAR, MPAD and AGCES data along with a mean and standard deviation of the variable as applied to the three simulations is taken from Reference 1. This same data is further analyzed in Table III.

## 5. Discussion

The Discussion Section of the NASA report (1) is included as Appendix I. The conclusion reached is that results compare well. Differences are attributable to hardware accuracy limitations or to possible differences in simulation models. In reviewing Figures 1 through 26 we believe the Bellcomm simulation data leads to similar conclusions.

A comparison of the simulation termination data in Table II illustrates good comparison among all five simulations for the non-spinning entries (cases two through six). The impact data is examined in more detail in Table III. Here the BC simulations are evaluated in terms of the mean and standard deviation based upon the other simulations.

Again for cases two through six one can consider the results as acceptable with little reservation. The spinning entries show the BC/DES to yield two larger deviations from the mean. They may be attributable to differences in models and rotational dynamics. The comparison between the DES and HES appears satisfactory except for the relative velocity calculation. Here one suspects analog computer inaccuracy.

In summary a comparison of the numerical results and an overall view of the time histories indicates that BC/HES is sufficiently accurate to warrant its application in generating data.

*I. Bogner*  
I. Bogner

*S. B. Watson*  
S. B. Watson

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Attachments: Appendix I

TABLE II - PARAMETERS AT 100,000. FT. ALTITUDE

| PARAMETER  | SIMULATION          | CASE/1  | 1A*     | 2       | 3       | 4       | 5       | 6       | 7       | 7A*     |
|--|---------------------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
| Altitude<br>(feet)   | AGCES               | 100,077 |         | 100,073 | 100,077 | 100,076 | 100,086 | 100,225 | 100,078 |         |
|  | NR                  | 100,000 |         | 100,000 | 100,000 | 100,000 | 100,000 | 100,000 | 100,000 |         |
|  | MPAD                | 100,612 |         | 99,267  | 100,121 | 100,343 | 99,898  | 100,211 | 99,943  |         |
|  | BC/DES              | 99,999  | 106,675 | 100,000 | 100,000 | 99,999  | 100,000 | 100,000 | 99,981  | 161,279 |
|  | BC/HES              |         | 106,752 | 99,968  | 99,968  | 99,968  | 99,968  | 99,968  |         | 161,280 |
| Time<br>(sec.)   | AGCES               | 387     |         | 389     | 659     | 743     | 657     | 664     | 159     |         |
|  | NR                  | 385     |         | 383     | 660     | 755     | 660     | 657     | 161     |         |
|  | MPAD                | 384     |         | 384     | 666     | 764     | 668     | 670     | 162     |         |
|  | BC/DES              | 382     | 376     | 381     | 660     | 754     | 660     | 659     | 160     | 90      |
|  | BC/HES              |         | 374     | 381     | 657     | 752     | 659     | 676     |         | 90      |
| Relative<br>Velocity<br>(ft./sec.)   | AGCES               | 5,312   |         | 5,199   | 3,122   | 3,156   | 2,847   | N.A.    | 4,982   |         |
|  | NR                  | 5,204   |         | 5,356   | 2,899   | 2,893   | 2,604   | 2,639   | 4,999   |         |
|  | MPAD                | 5,322   |         | 5,213   | 2,830   | 2,859   | 2,478   | 3,104   | 4,951   |         |
|  | MEAN                | 5,279   |         | 5,256   | 2,950   | 2,969   | 2,643   | 2,872   | 4,977   |         |
|  | STD. DEVI-<br>ATION | 53.43   |         | 70.94   | 124.61  | 132.72  | 153.15  | 232.5   | 19.87   |         |
| Latitude<br>(degrees)  | BC/DES              | 5,339   | 6,541   | 5,282   | 2,889   | 2,882   | 2,595   | 2,812   | 4,899   | 27,780  |
|  | BC/HES              |         | 6,513   | 5,198   | 2,903   | 2,882   | 2,595   | 2,793   |         | 27,701  |
|  | AGCES               | 32.45   |         | 32.98   | 30.87   | 29.93   | 30.76   | 30.41   | 32.58   |         |
|  | NR                  | 32.44   |         | 32.95   | 30.82   | 29.79   | 30.90   | 30.95   | 32.59   |         |
|  | MPAD                | 32.44   |         | 32.97   | 30.81   | 29.72   | 30.89   | 30.66   | 32.58   |         |
| Longitude<br>(degrees)   | MEAN                | 32.44   |         | 32.97   | 30.83   | 29.81   | 30.85   | 30.67   | 32.58   |         |
|  | STD. DEVI-<br>ATION | .006    |         | .013    | .026    | .087    | .063    | .221    | 0.0     |         |
|  | BC/DES              | 32.45   | 32.46   | 32.98   | 30.84   | 29.83   | 30.92   | 30.89   | 32.58   | 32.36   |
|  | BC/HES              |         | 32.46   | 32.98   | 30.87   | 29.90   | 30.94   | 30.76   |         | 32.35   |
|  | AGCES               | -70.83  |         | -70.81  | -58.88  | -54.68  | -59.28  | -57.80  | -85.03  |         |
| Longitude<br>(degrees)   | NR                  | -70.93  |         | -71.08  | -58.63  | -53.79  | -59.07  | -59.35  | -84.84  |         |
|  | MPAD                | -70.94  |         | -70.95  | -58.57  | -53.43  | -59.00  | -57.74  | -84.82  |         |
|  | MEAN                | -70.90  |         | -70.95  | -58.69  | -53.97  | -59.12  | -58.30  | -84.90  |         |
|  | STD. DEVI-<br>ATION | .049    |         | .110    | .134    | .525    | .119    | .745    | .094    |         |
|  | BC/DES              | -71.15  | -71.26  | -71.16  | -58.74  | -53.95  | -59.19  | -59.04  | -84.98  | -88.29  |
|  | BC/HES              |         | -71.34  | -71.22  | -58.93  | -54.02  | -59.22  | -58.40  |         | -88.31  |
| *Cases 1A and 7A are similar to cases 1 and 7. Termination occurs at greater than the 100,000. ft. altitude due to scaling (high G) limitations. BC/DES termination for those altitudes are presented for comparison purposes. |                     |         |         |         |         |         |         |         |         |         |

TABLE III - COMPARISON OF PARAMETERS AT 100,000. FT. ALTITUDE

| PARAMETER              | CASE/1        | 1A*           | 2             | 3             | 4              | 5             | 6              | 7             | 7A*           |
|------------------------|---------------|---------------|---------------|---------------|----------------|---------------|----------------|---------------|---------------|
| Rel. Vel. (ft/sec)     |               |               |               |               |                |               |                |               |               |
| Mean                   | 5279.         |               | 5256.         | 2950.         | 2969.          | 2643.         | 2872.          | 4977.         |               |
| Std. Dev. ( $\sigma$ ) | 53.49         |               | 70.94         | 124.61        | 132.72         | 153.15        | 232.5          | 19.87         |               |
| BC/DES                 | 5339.         | 6541.         | 5282.         | 2889.         | 2882.          | 2595.         | 2812.          | 4899.         | 27780.        |
| BC/HES                 |               | 6531.         | 5198.         | 2903.         | 2882.          | 2595.         | 2793.          |               | 27701.        |
| DES $\Delta$           | +1.1 $\sigma$ |               | +0.4 $\sigma$ | -0.5 $\sigma$ | -1.1 $\sigma$  | -0.3 $\sigma$ | -0.3 $\sigma$  | -3.9 $\sigma$ |               |
| HES $\Delta$           |               | -0.2 $\sigma$ | -0.8 $\sigma$ | -0.4 $\sigma$ | -1.1 $\sigma$  | -0.3 $\sigma$ | -0.3 $\sigma$  |               | -4.0 $\sigma$ |
| $\delta$               |               |               |               |               |                |               |                |               |               |
| Lat. (degrees)         |               |               |               |               |                |               |                |               |               |
| Mean                   | 32.44         |               | 32.97         | 30.83         | 29.81          | 30.85         | 30.67          | 32.58         |               |
| Std. Dev. ( $\sigma$ ) | .006          |               | .013          | .026          | .087           | .063          | .221           | 0.0           |               |
| BC/DES                 | 32.45         | 32.46         | 32.98         | 30.84         | 29.83          | 30.92         | 30.89          | 32.58         | 32.36         |
| BC/HES                 |               | 32.46         | 32.98         | 30.87         | 29.90          | 30.94         | 30.76          |               | 32.35         |
| DES $\Delta$           | +1.7 $\sigma$ |               | +0.8 $\sigma$ | +0.4 $\sigma$ | +0.2 $\sigma$  | +1.1 $\sigma$ | +1.0 $\sigma$  | 0.0 $\sigma$  |               |
| HES $\Delta$           |               | 0.0 $\sigma$  | +0.8 $\sigma$ | +1.5 $\sigma$ | +1.0 $\sigma$  | +1.4 $\sigma$ | +0.4 $\sigma$  |               | ---           |
| $\delta$               |               |               |               |               |                |               |                |               |               |
| Long. (degrees)        |               |               |               |               |                |               |                |               |               |
| Mean                   | -70.90        |               | -70.95        | -58.69        | -53.97         | -59.12        | -58.30         | -84.9         |               |
| Std. Dev. ( $\sigma$ ) | .049          |               | .110          | .134          | .525           | .119          | .745           | .094          |               |
| BC/DES                 | -71.15        | -71.26        | -71.16        | -58.74        | -53.95         | -59.19        | -59.04         | -84.98        | -88.29        |
| BC/HES                 |               | -71.34        | -71.22        | -58.93        | -54.02         | -59.22        | -58.40         |               | -88.31        |
| DES $\Delta$           | -5.1 $\sigma$ |               | -1.9 $\sigma$ | -0.4 $\sigma$ | +0.04 $\sigma$ | -0.6 $\sigma$ | -1.0 $\sigma$  | +0.9 $\sigma$ |               |
| HES $\Delta$           |               | -1.6 $\sigma$ | -2.5 $\sigma$ | -1.8 $\sigma$ | -0.1 $\sigma$  | -0.8 $\sigma$ | -0.13 $\sigma$ |               | -0.2 $\sigma$ |
| $\delta$               |               |               |               |               |                |               |                |               |               |

DES  $\Delta$  = (BC/DES - Mean) in units of Std. Dev.HES  $\Delta$  = (BC/HES - Mean) in units of Std. Dev. $\delta$  = (BC/HES - BC/DES) in units of Std. Dev.

\*See footnote on Table II.

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REFERENCES

1. Reentry Simulation Comparison by V. W. Voybeck and J. Mac Parks, Lockheed Electronics Company, June 19, 1968. NASA Action Document AD30-617-20.



APPENDIX I

DISCUSSION (From Reference)

The NR simulation was initialized at  $97.84^\circ$  east longitude instead of at  $97.34^\circ$  west longitude as used in the other two simulations. Since the simulation models are independent of longitude, the NR data was translated to facilitate presentation and comparison of data so that the initial longitude agreed with that of the other two simulations.

In Case 2 the NR simulation was flown with lift vector at  $90^\circ$  to the south ( $270^\circ$  in spacecraft coordinates) instead of at  $90^\circ$  to the north as were the other two simulations. To facilitate presentation and comparison of data for this case, the distance traveled out-of-plane to the impact point was transferred from south of the trajectory plane. The trajectory plane was defined by the impact latitude for the rolling entry case (Case 1). Though some error results here due to earth oblateness, this is considered small.

Data comparison is considered good in all cases, with the qualifications noted above. It is felt that all remaining discrepancies which fall outside the range of hardware accuracy limitations can be accounted for with a more detailed comparison of simulation models.

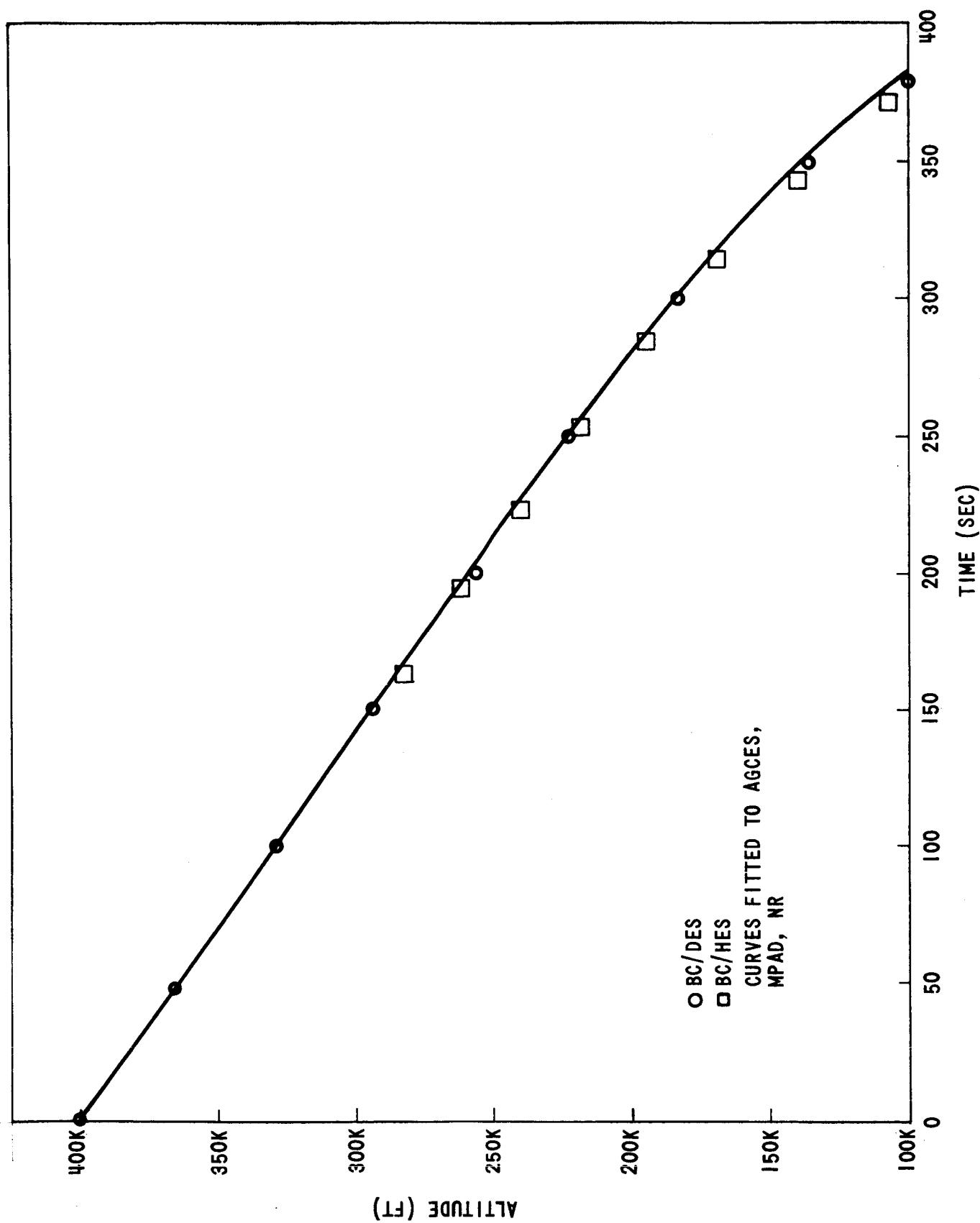


FIGURE 1 - ALTITUDE vs. TIME - CASE 1 (ROLL 20°/SEC)

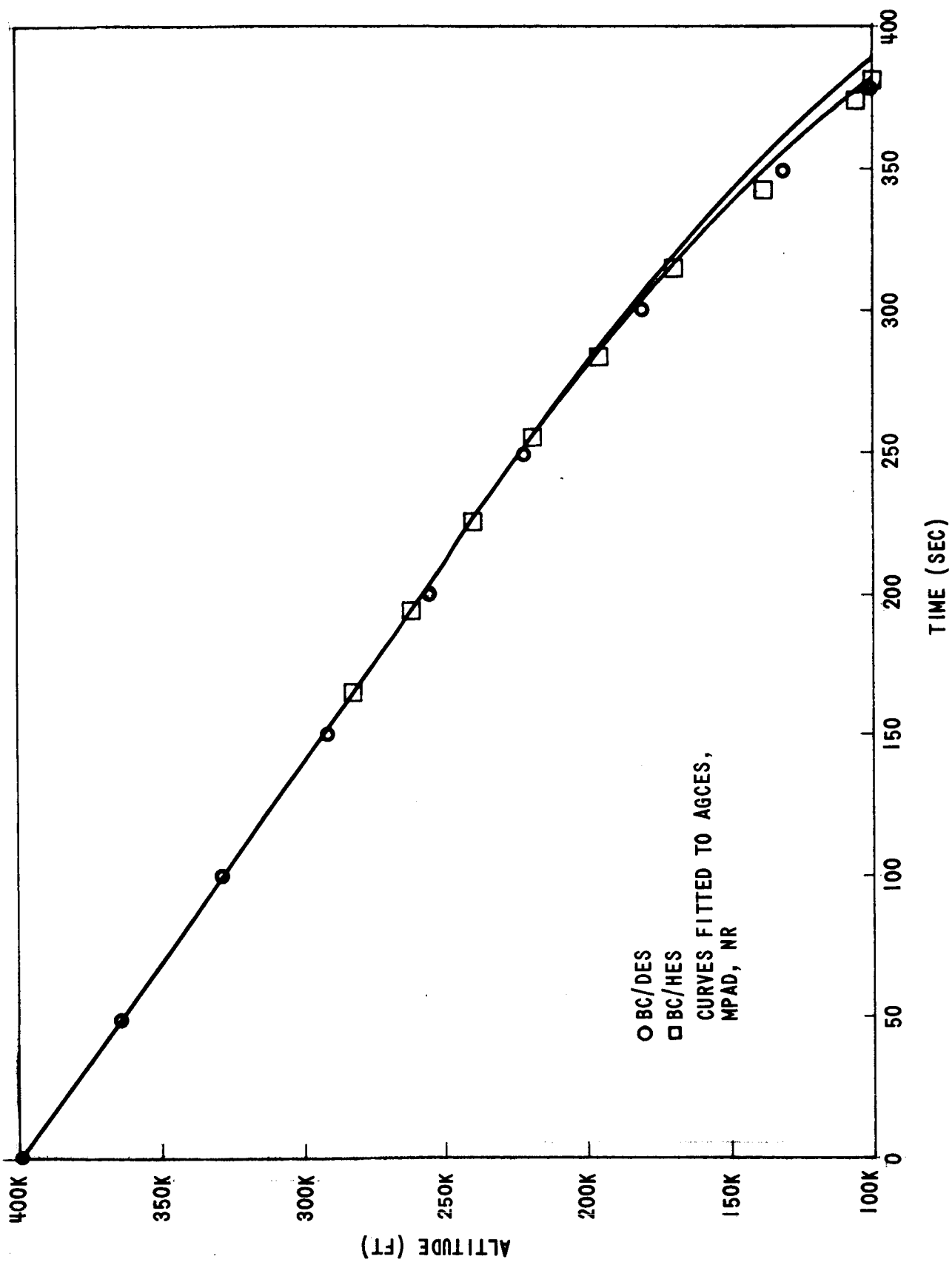


FIGURE 2 - ALTITUDE vs. TIME - CASE 2 (LIFT 90°)

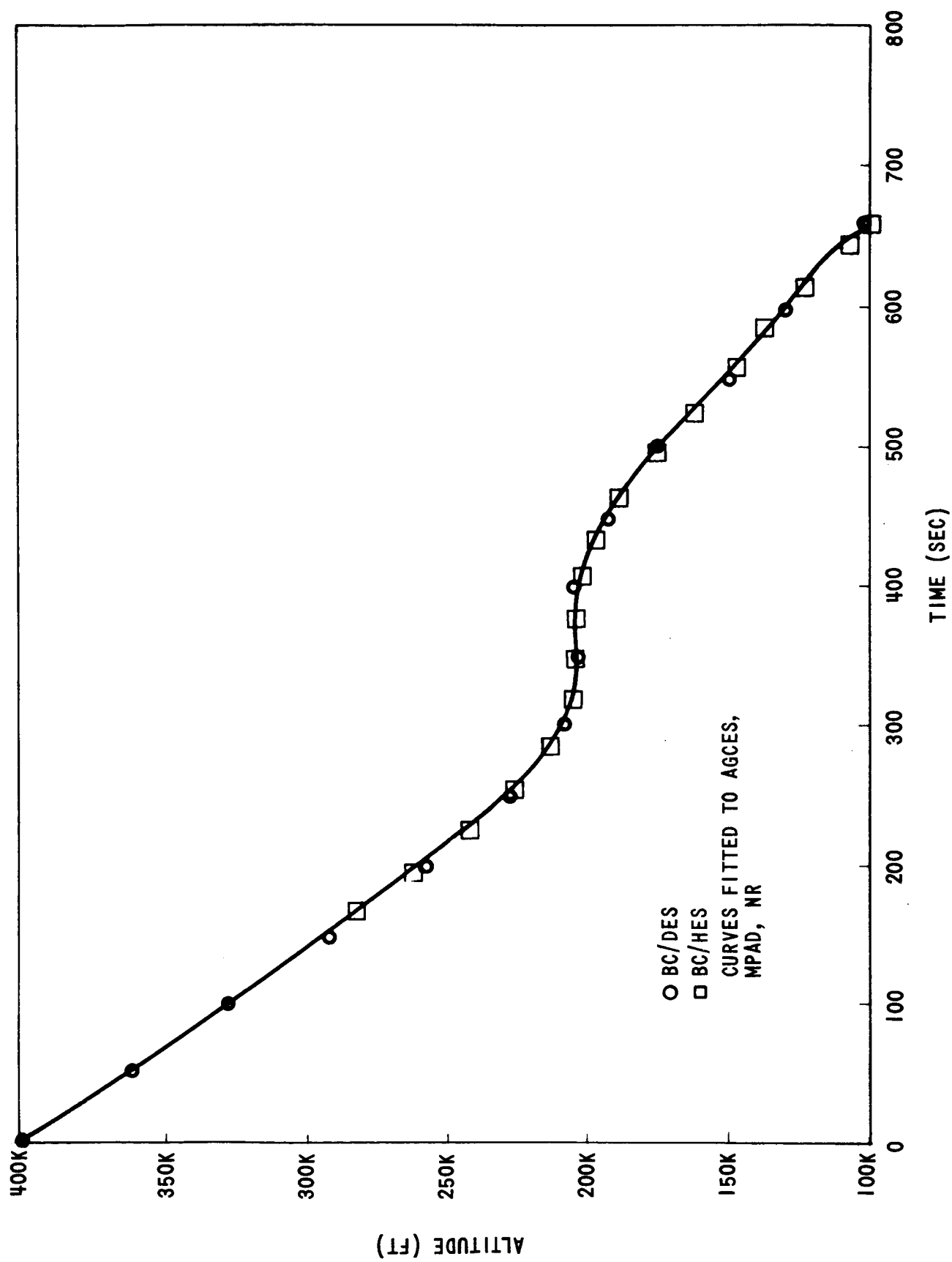


FIGURE 3 - ALTITUDE vs. TIME - CASE 3 (LIFT UP)

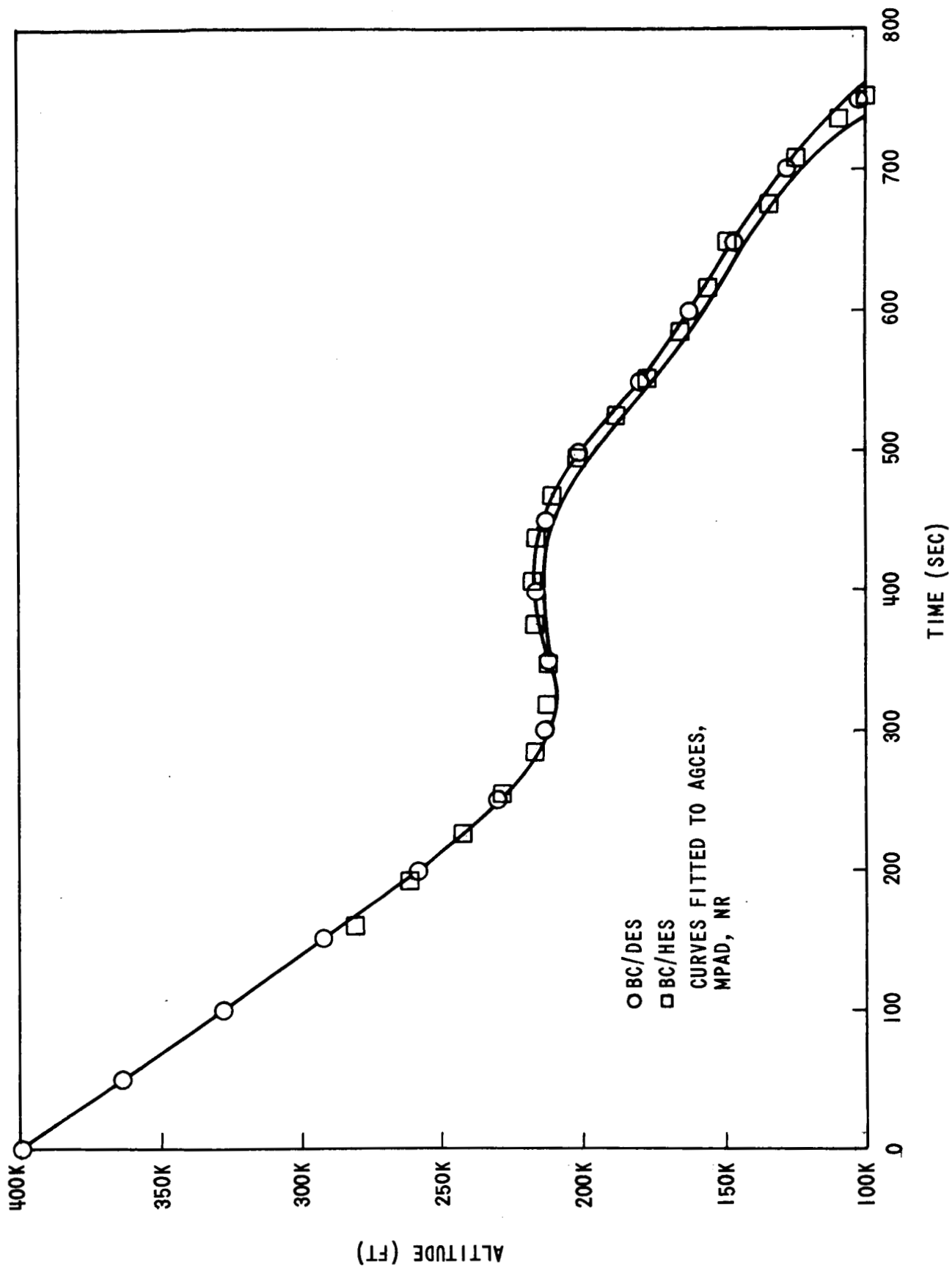


FIGURE 4 - ALTITUDE vs. TIME - CASE 4 (LIFT UP)

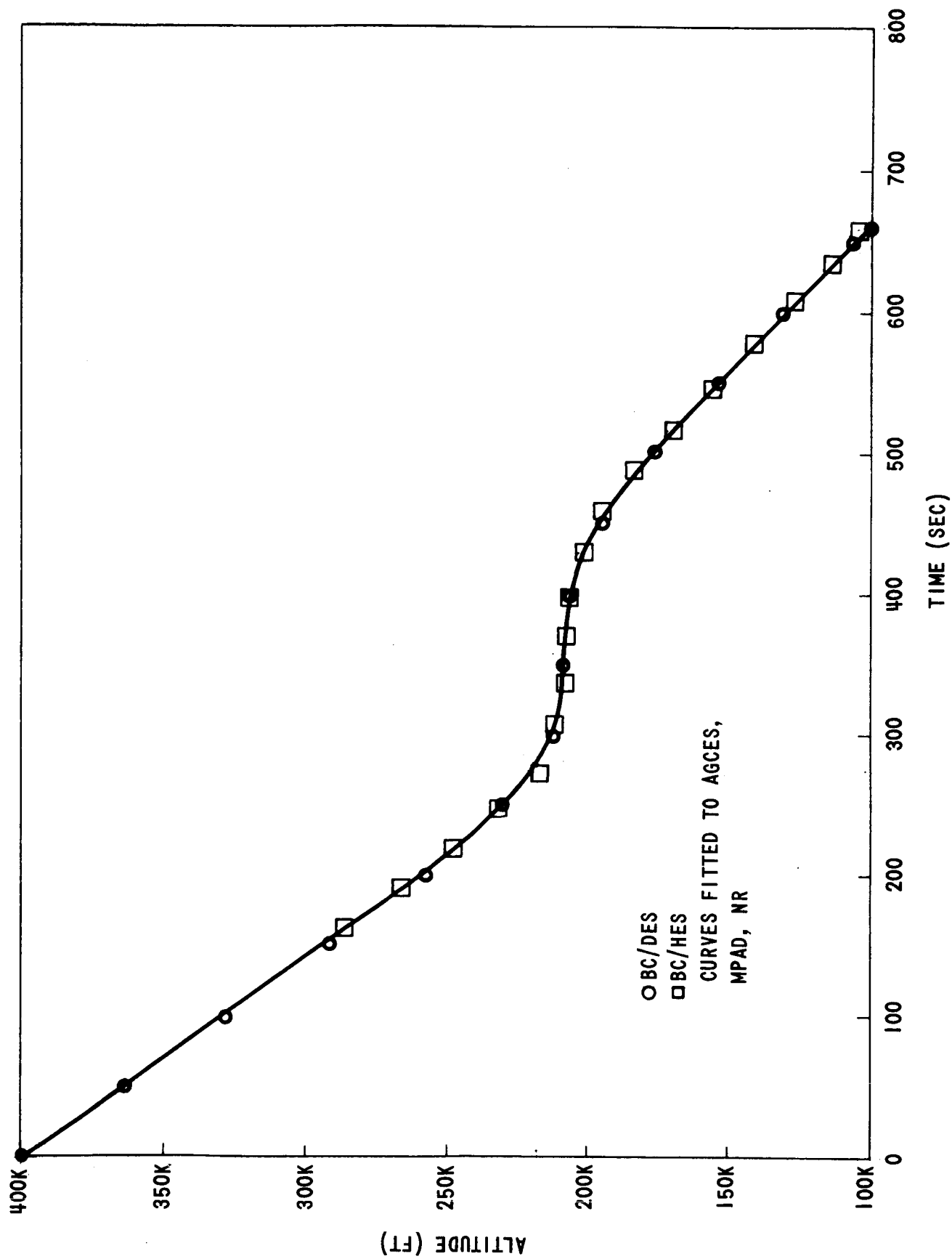


FIGURE 5 - ALTITUDE vs. TIME - CASE 5 (LIFT UP)

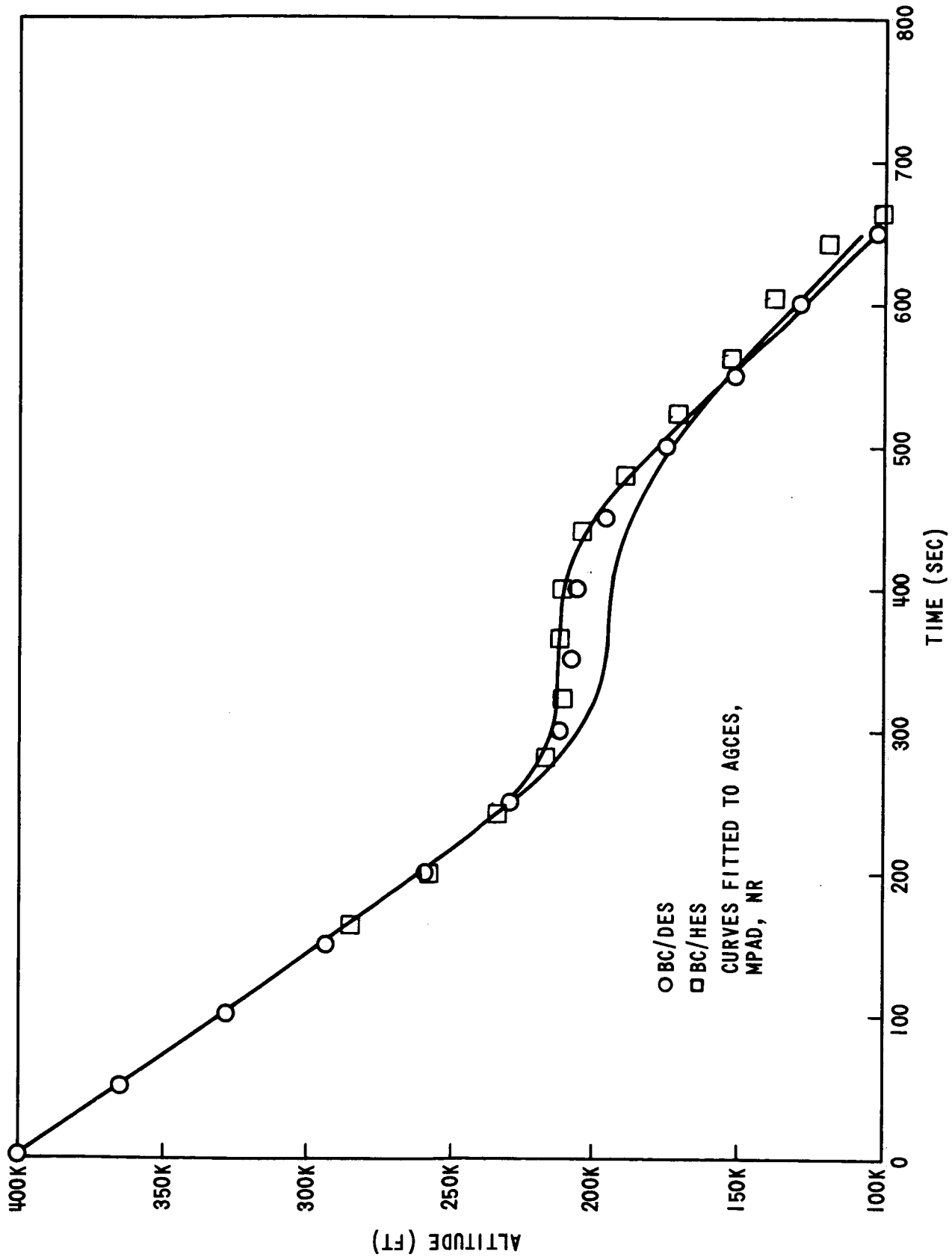


FIGURE 6 - ALTITUDE vs. TIME - CASE 6 (LIFT UP)

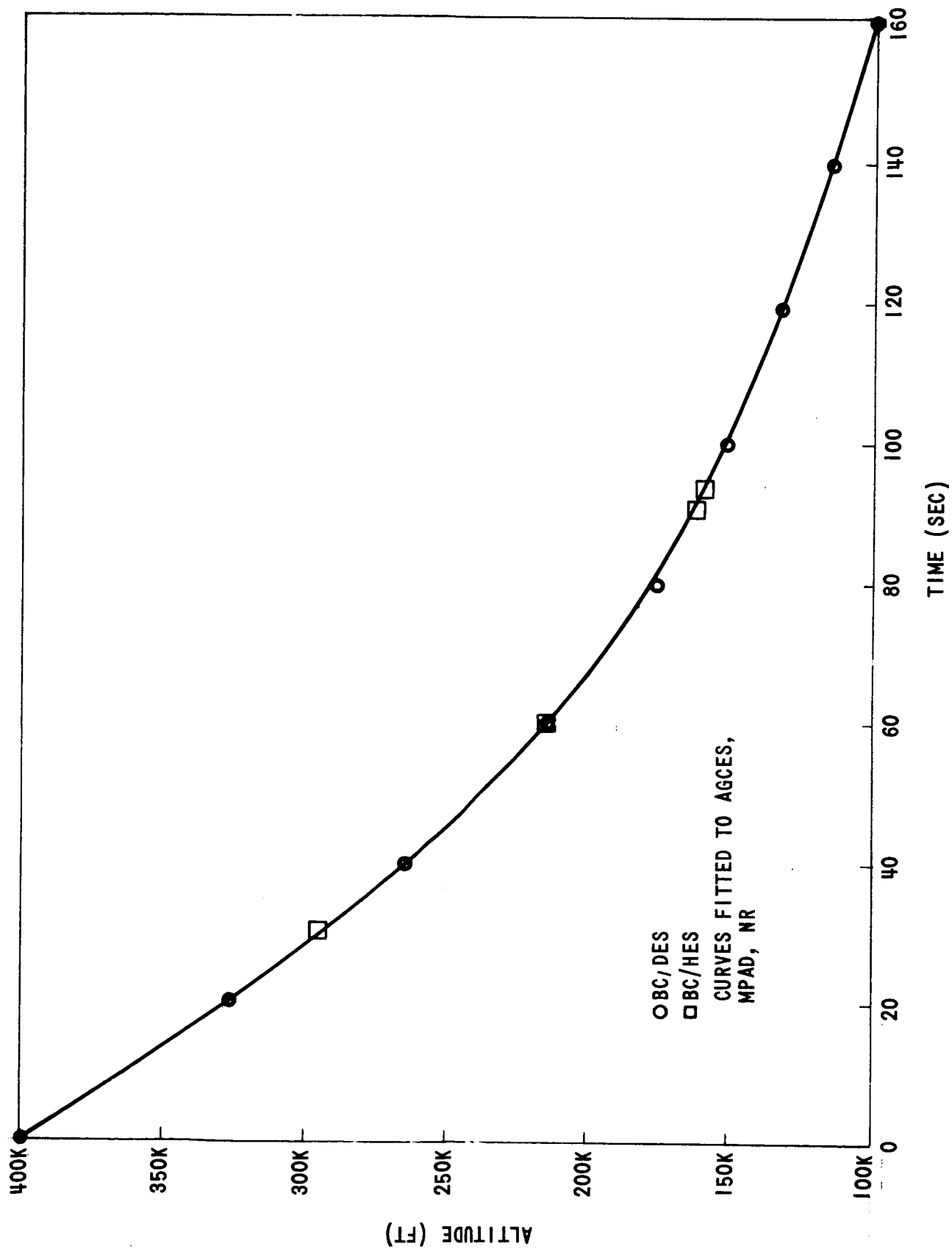


FIGURE 7 - ALTITUDE vs. TIME - CASE 7 (ROLL 20°/SEC)



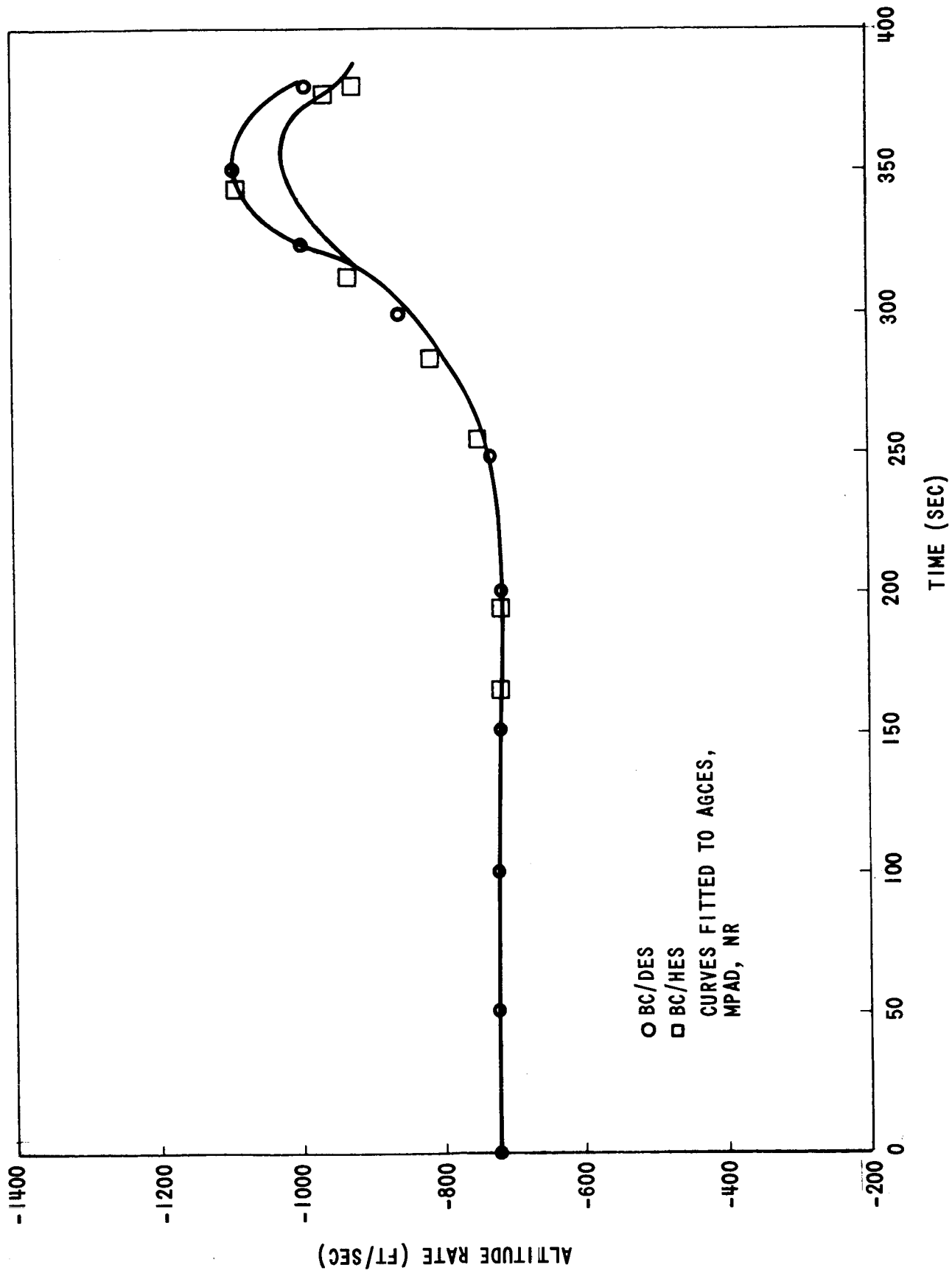


FIGURE 8 - ALTITUDE RATE vs. TIME - CASE 2 (LIFT 90°)

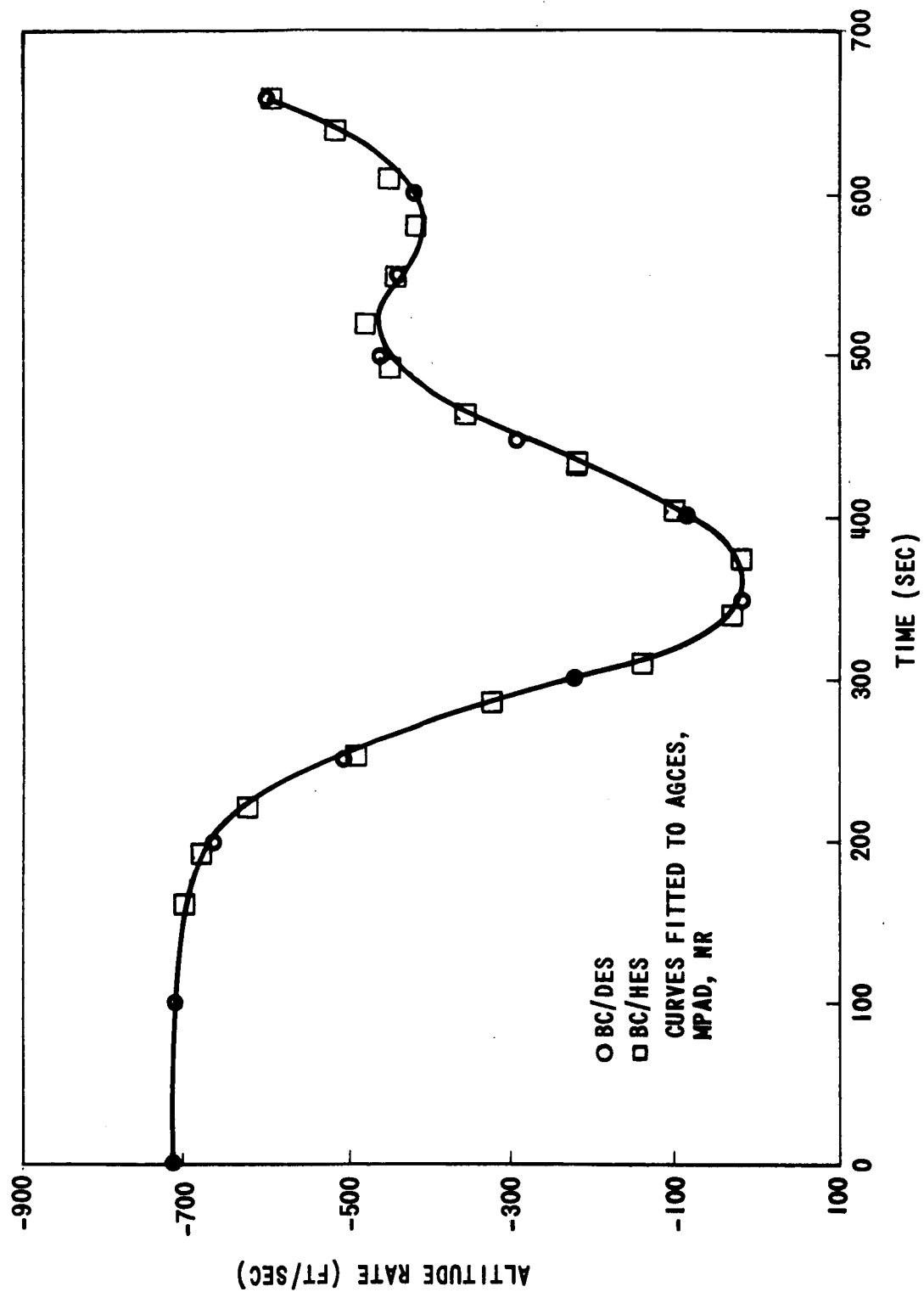


FIGURE 9 - ALTITUDE RATE vs. TIME - CASE 3 (LIFT UP)

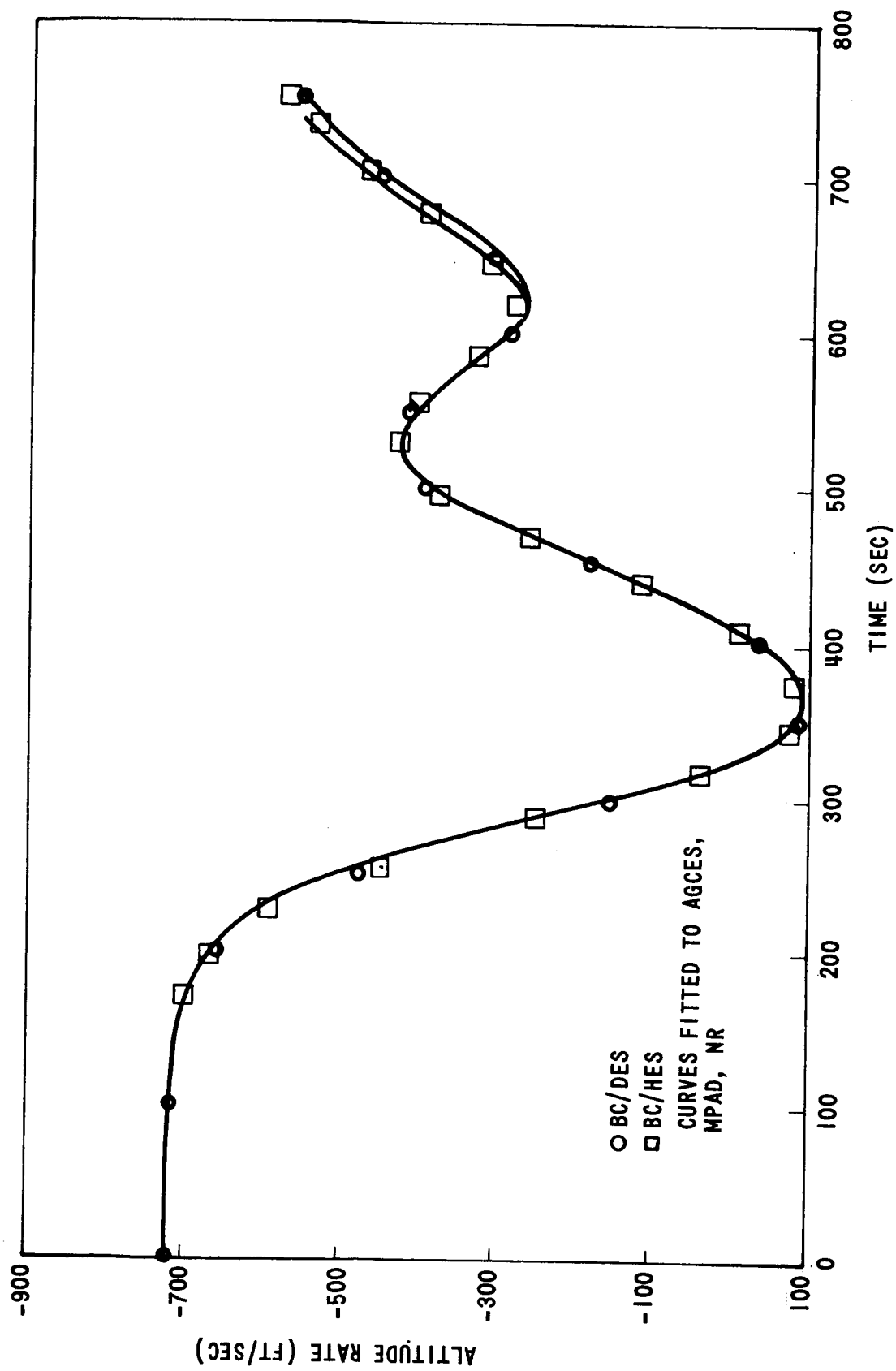


FIGURE 10 - ALTITUDE RATE vs. TIME - CASE 4 (LIFT UP)

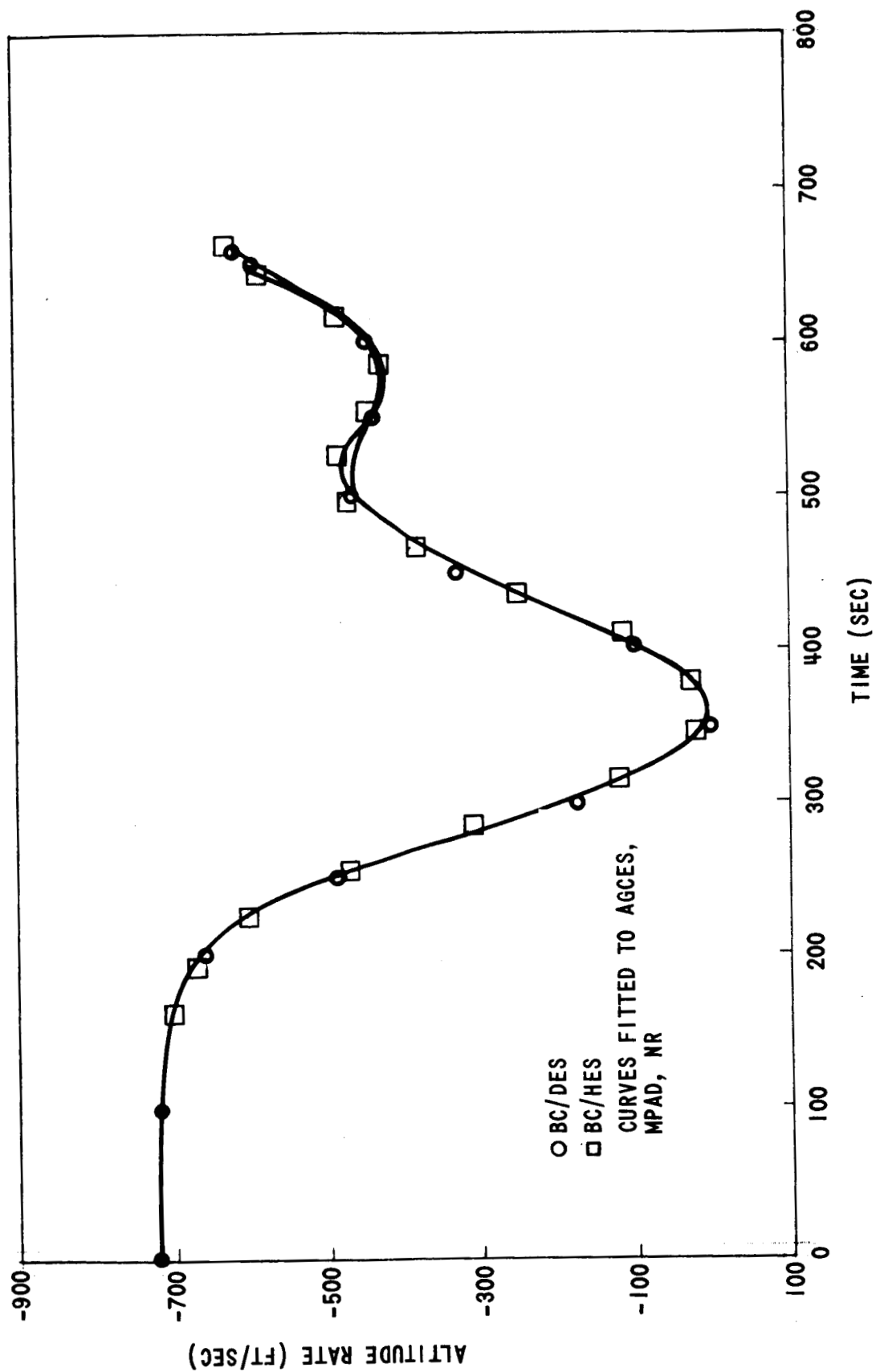


FIGURE 11 - ALTITUDE RATE vs. TIME - CASE 5 (LIFT UP)

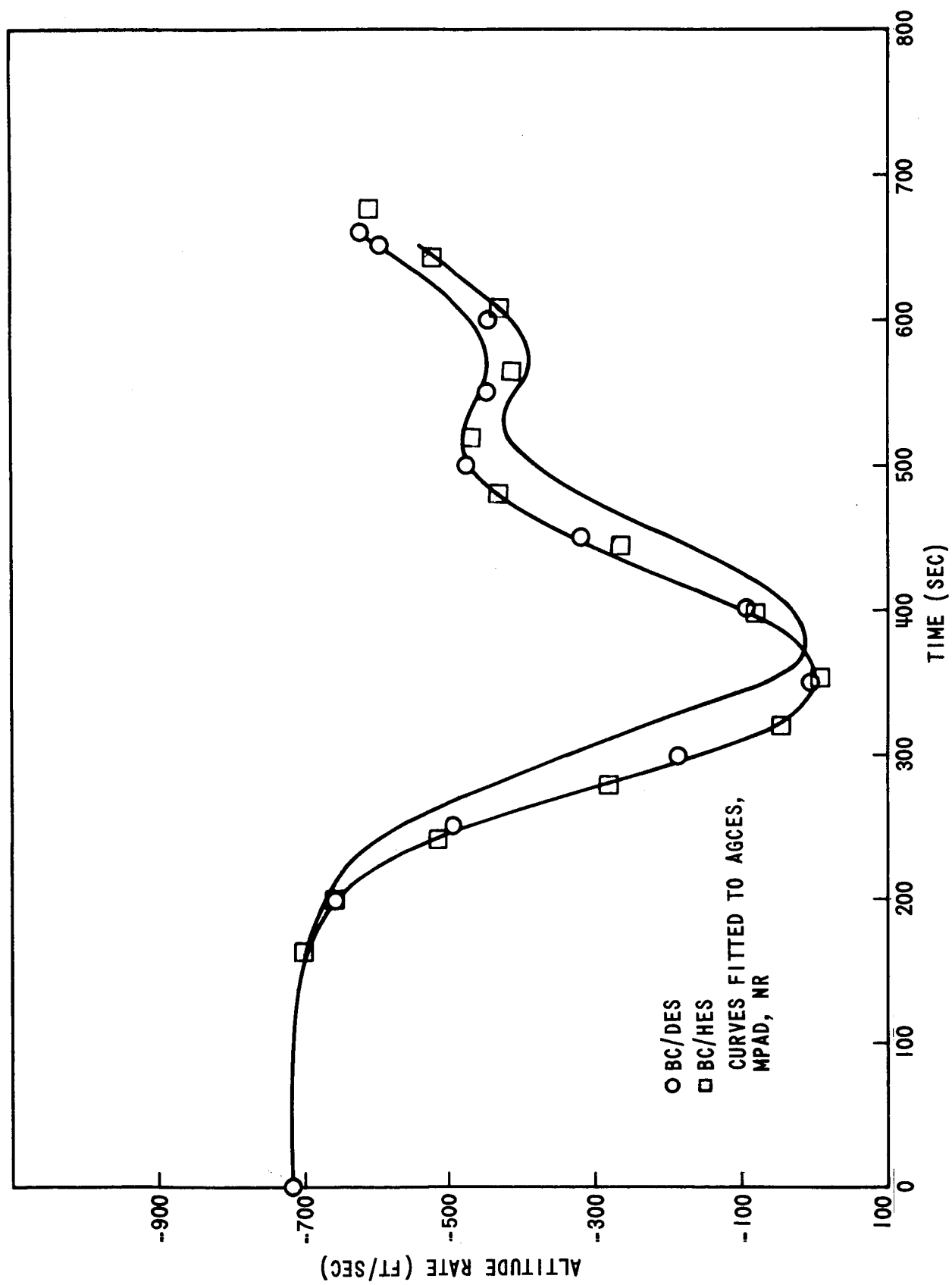


FIGURE 12 - ALTITUDE RATE vs. TIME - CASE 6 (LIFT UP)

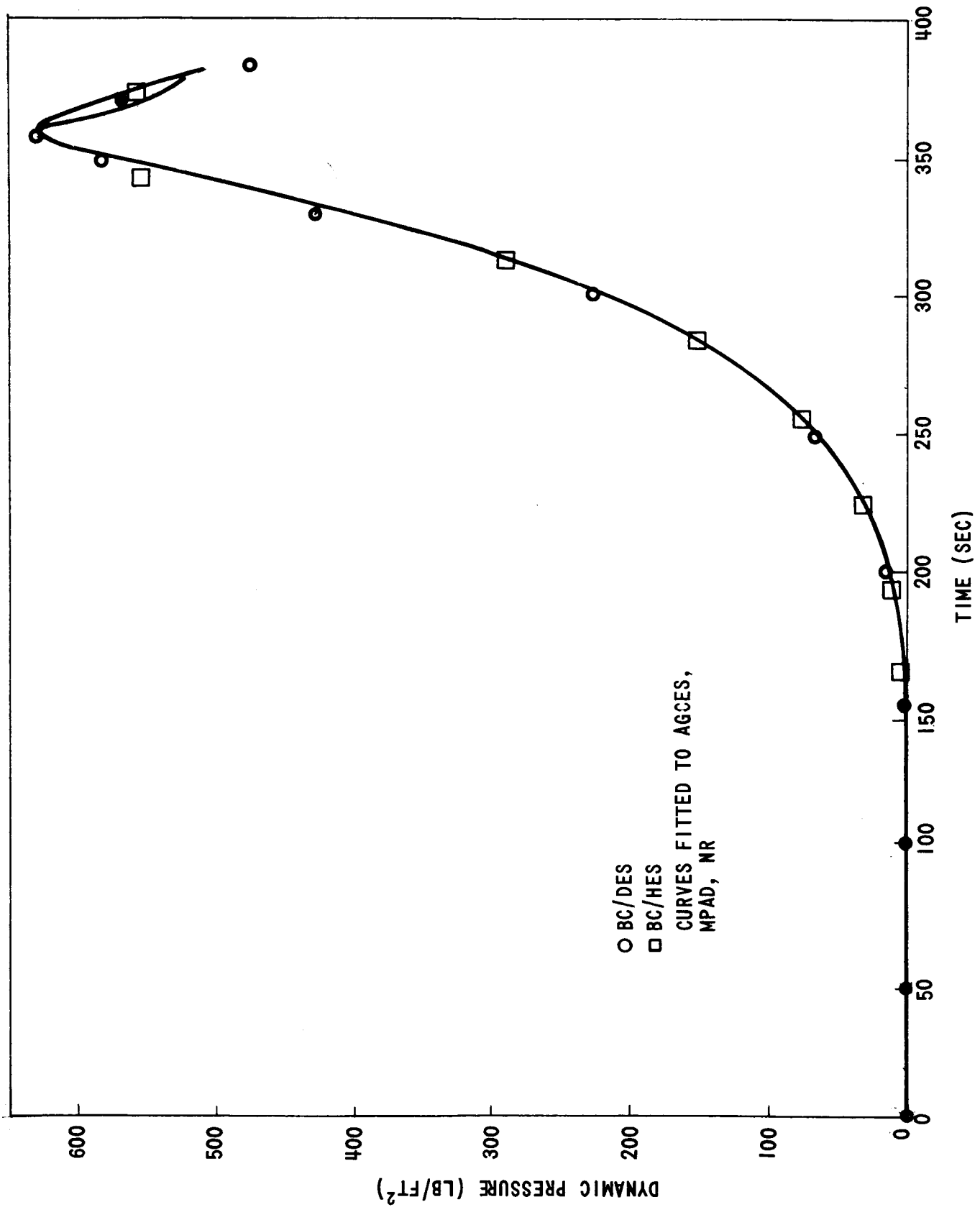


FIGURE 13 - DYNAMIC PRESSURE vs. TIME - CASE 1 (ROLL 20°/SEC)

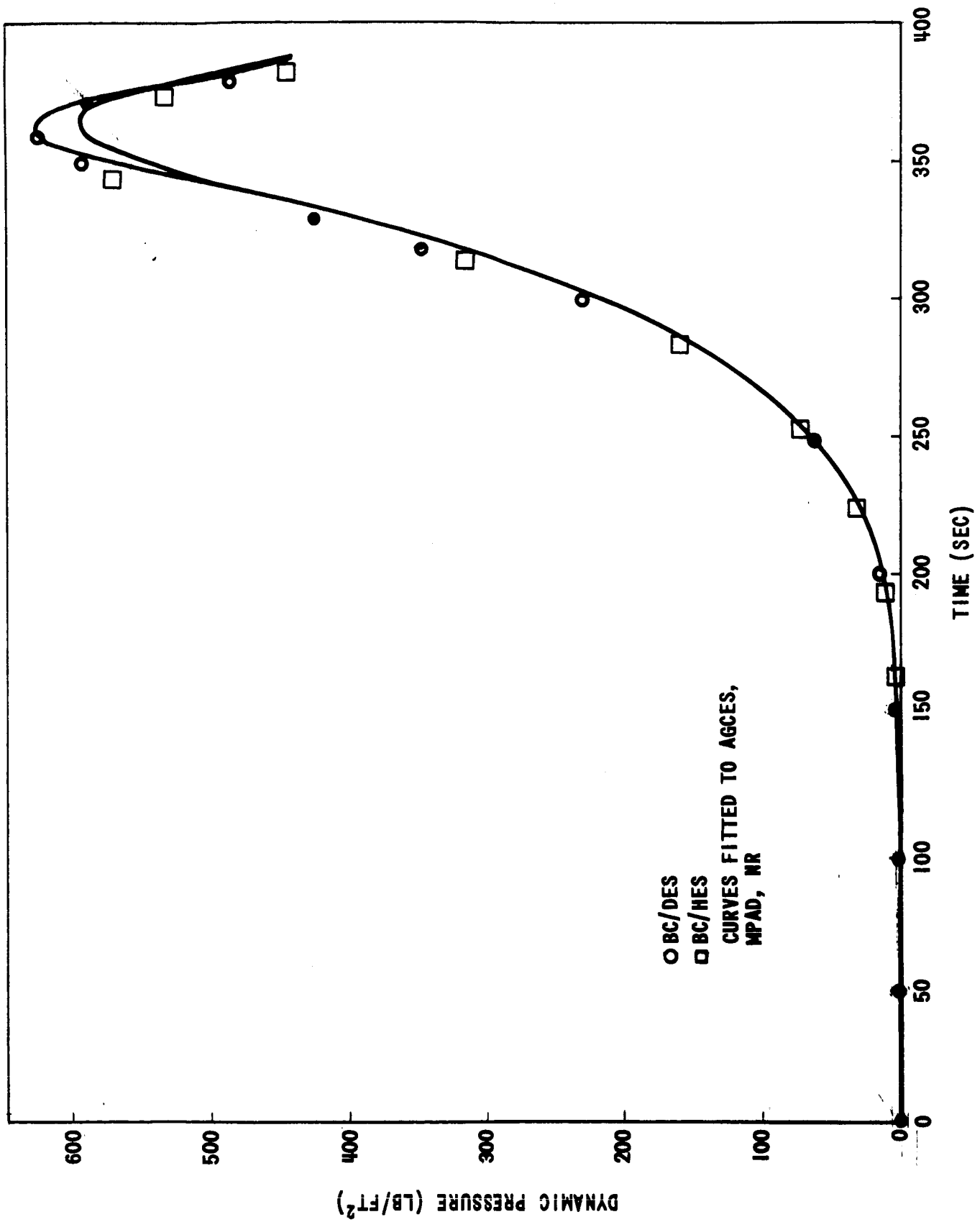


FIGURE 14 - DYNAMIC PRESSURE vs. TIME - CASE 2 (LIFT 90°)

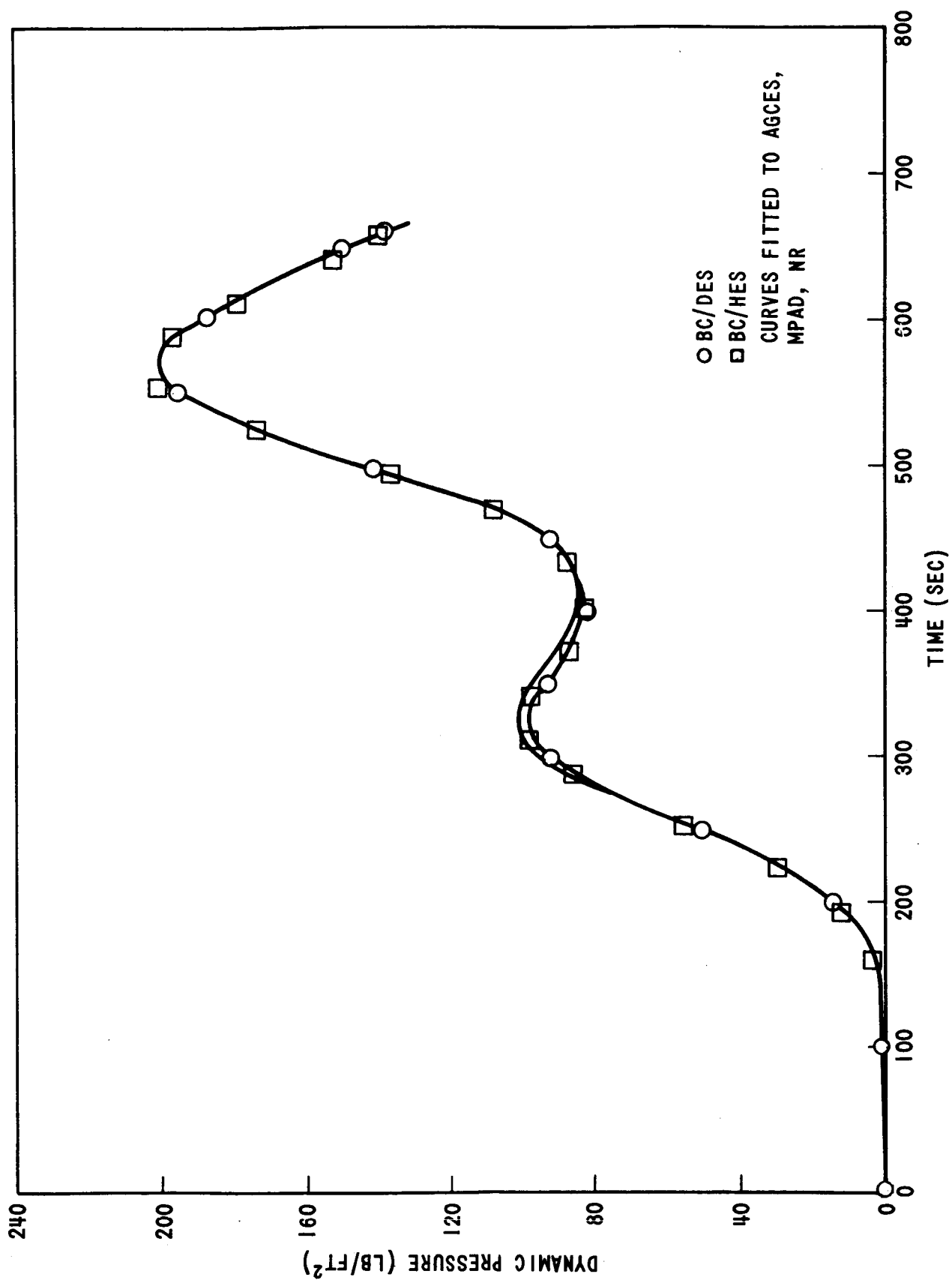


FIGURE 15 - DYNAMIC PRESSURE vs. TIME - CASE 3 (LIFT UP)



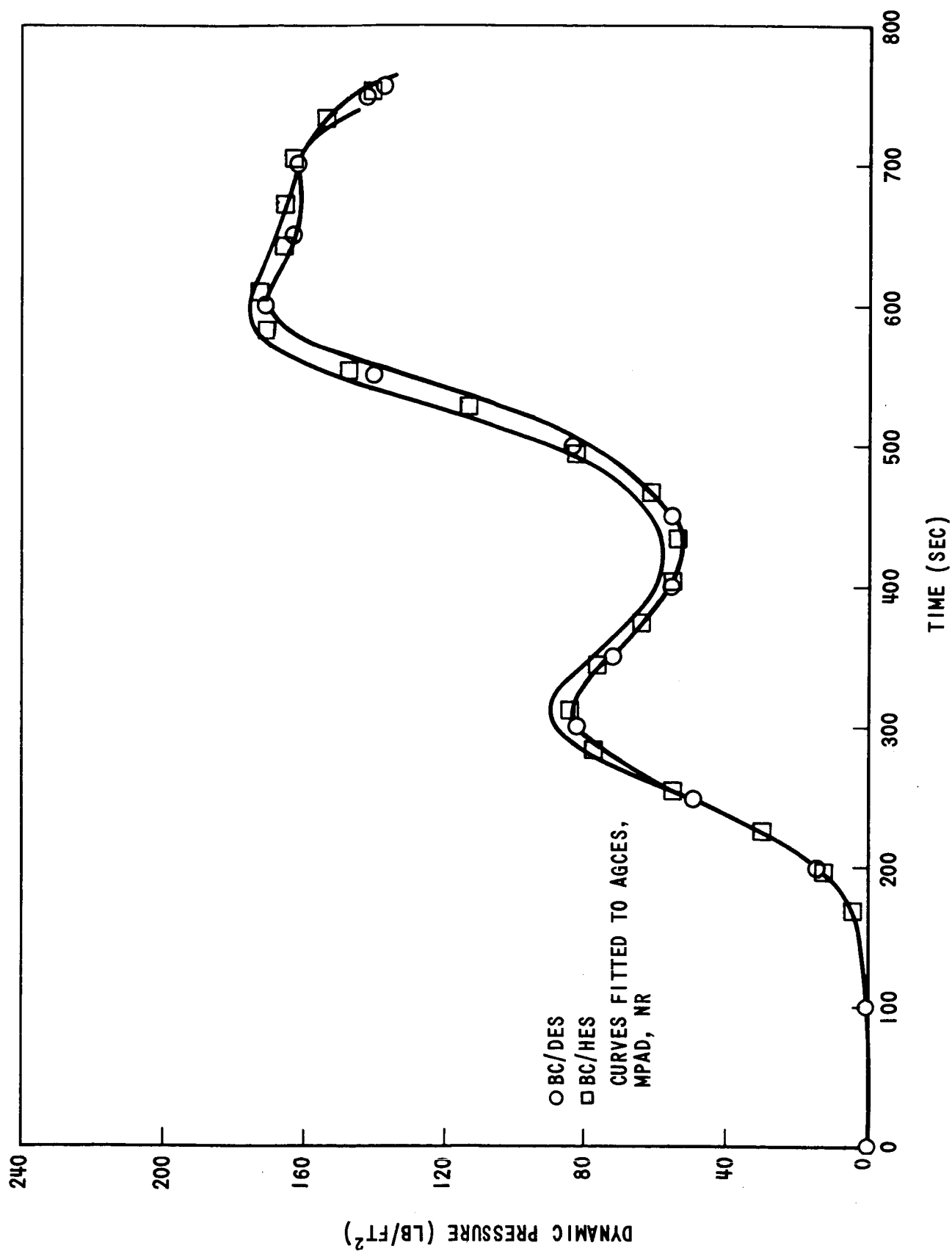


FIGURE 16 - DYNAMIC PRESSURE vs. TIME - CASE 4 (LIFT UP)

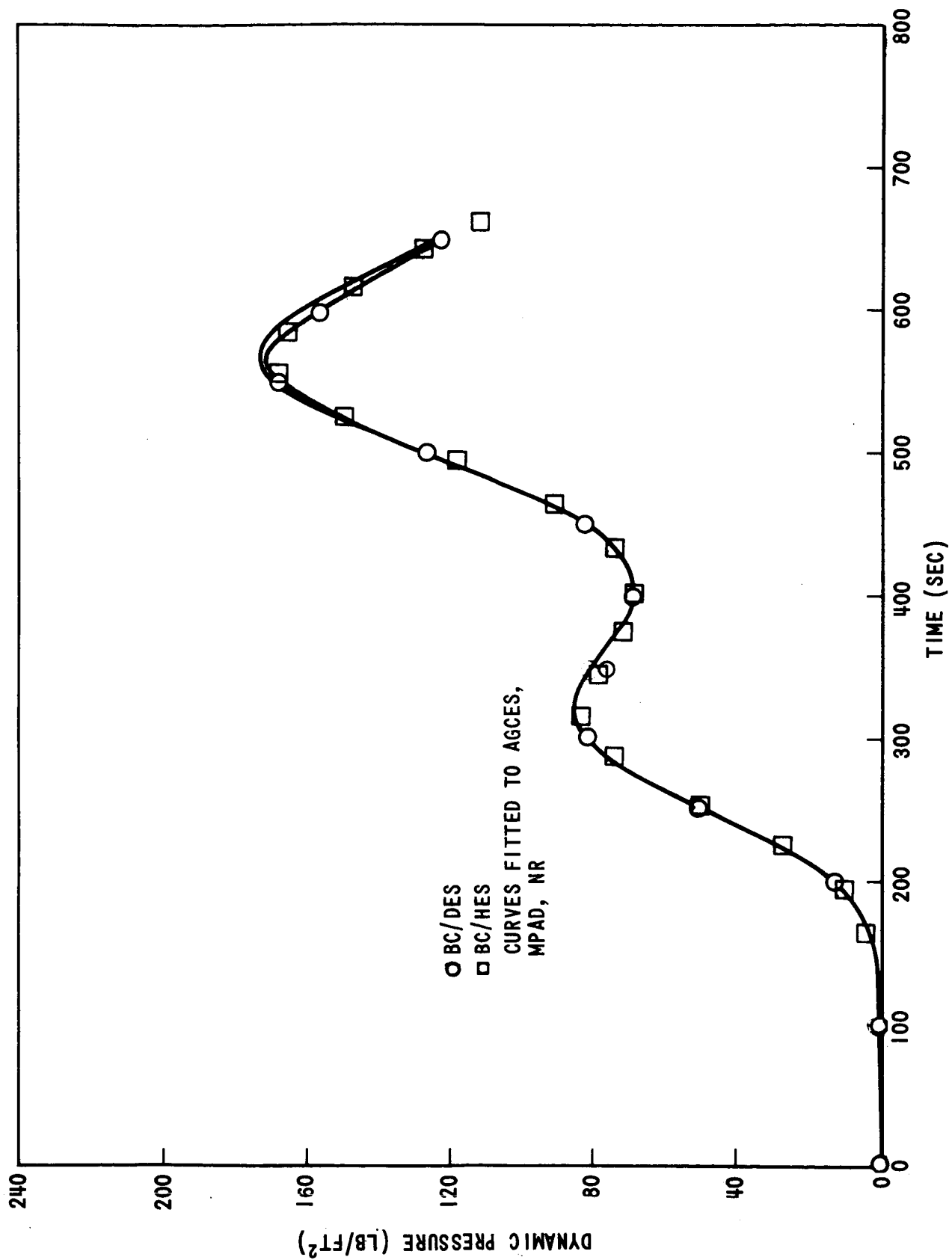


FIGURE 17 - DYNAMIC PRESSURE vs. TIME - CASE 5 (LIFT UP)

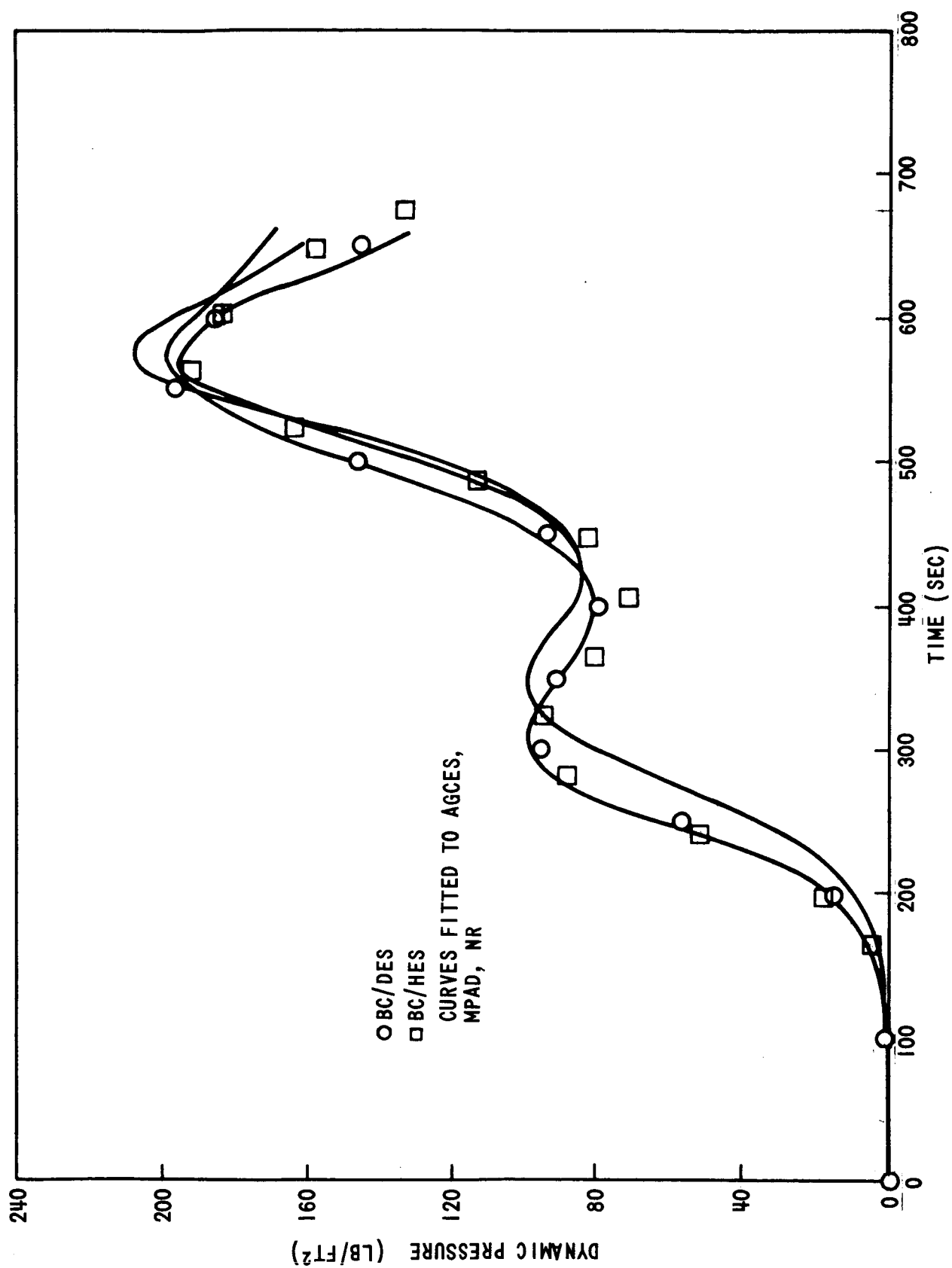


FIGURE 18 - DYNAMIC PRESSURE vs. TIME - CASE 6 (LIFT UP)

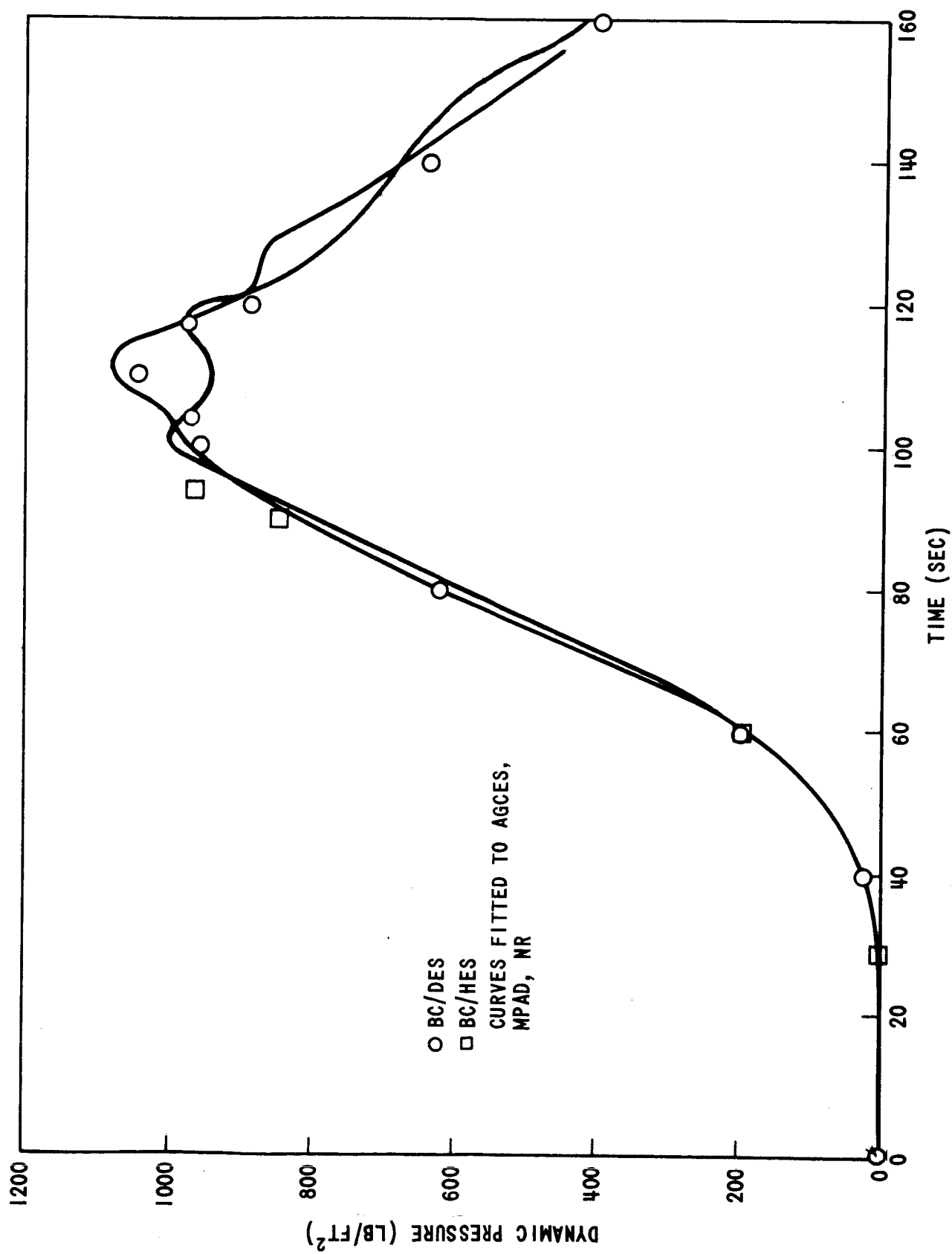


FIGURE 19 - DYNAMIC PRESSURE vs. TIME - CASE 7 (ROLL 20°/SEC)

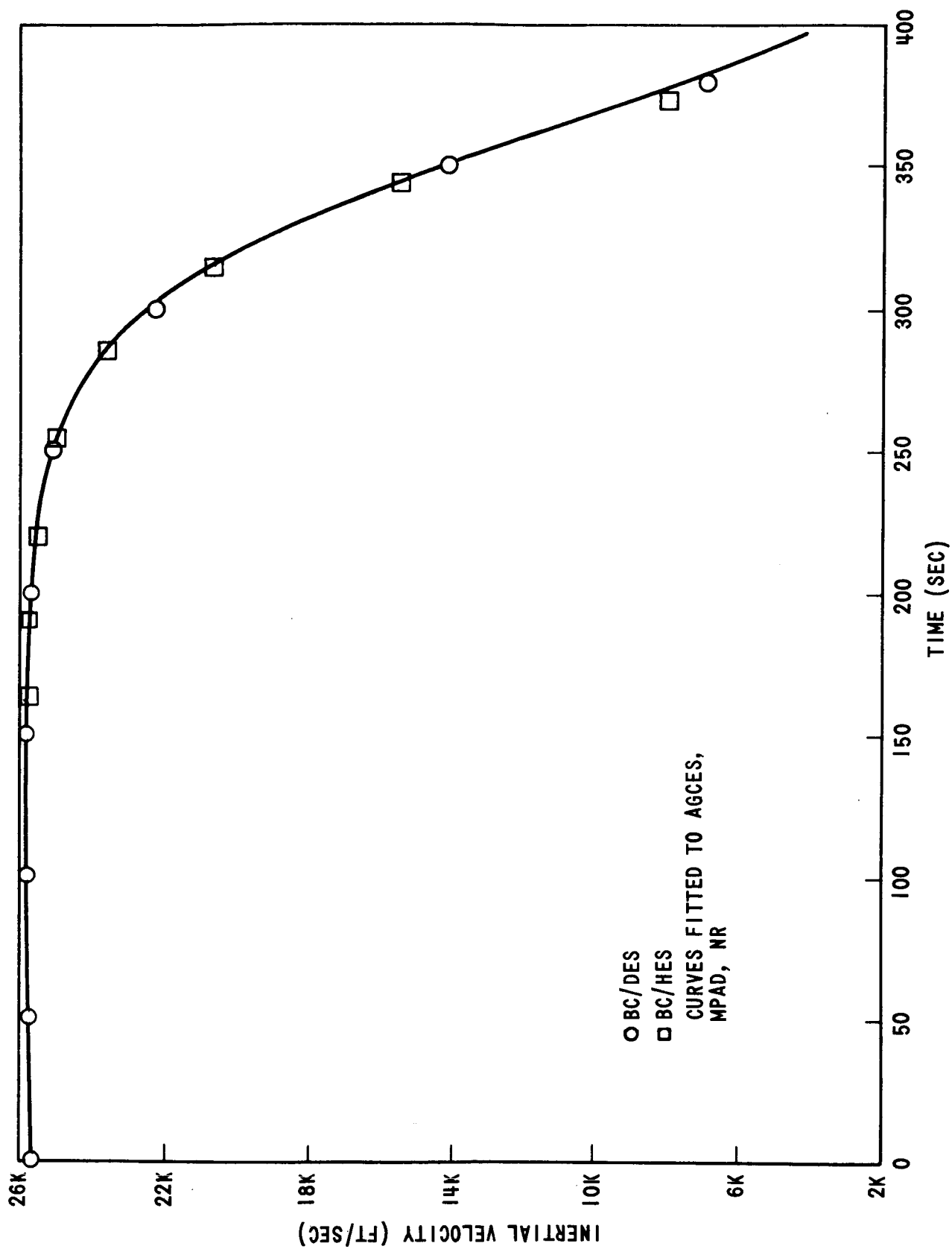


FIGURE 20 - INERTIAL VELOCITY vs. TIME - CASE 1 (ROLL 20°/SEC)

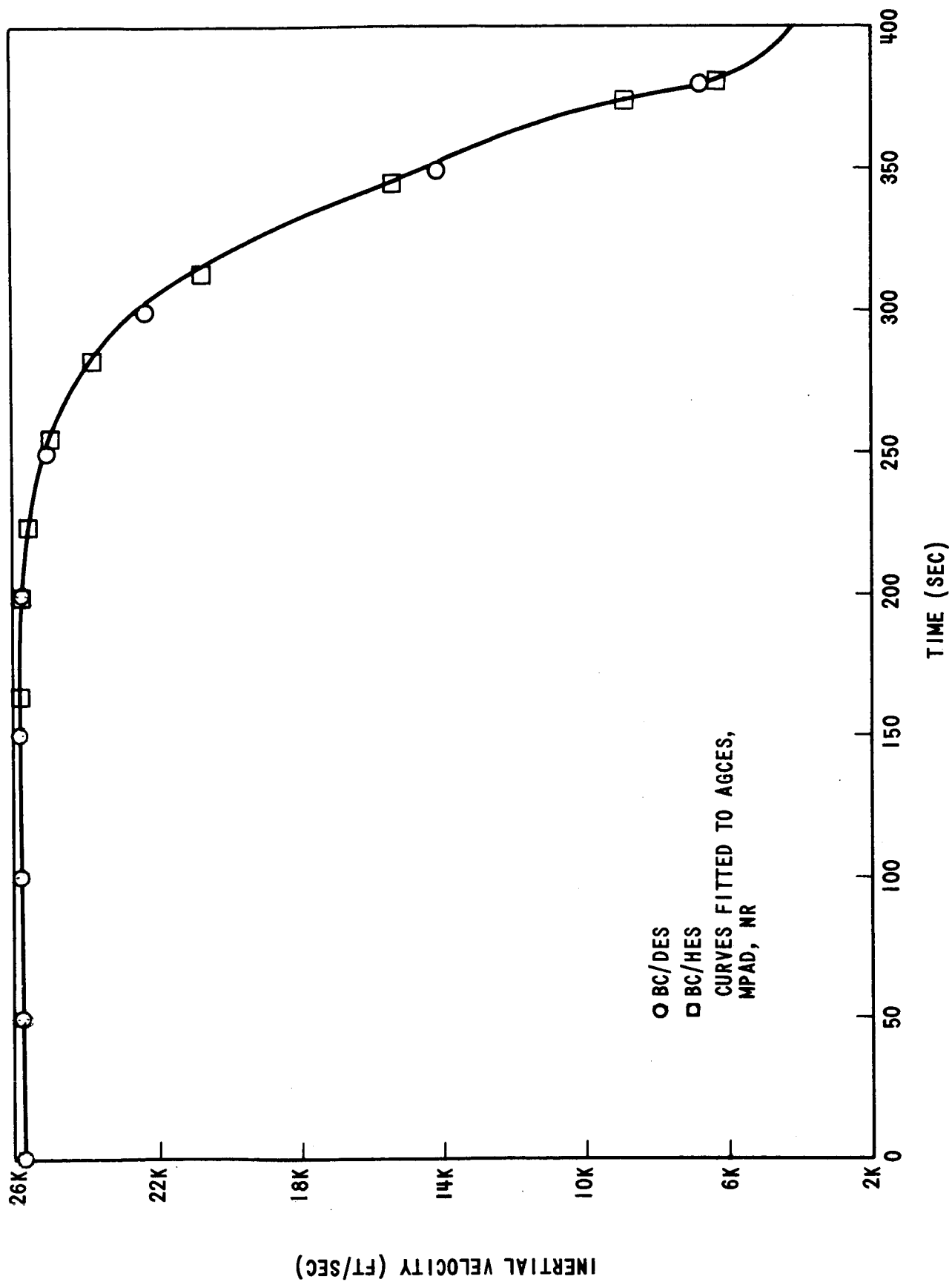


FIGURE 21 - INERTIAL VELOCITY vs. TIME - CASE 2 (LIFT 90°)

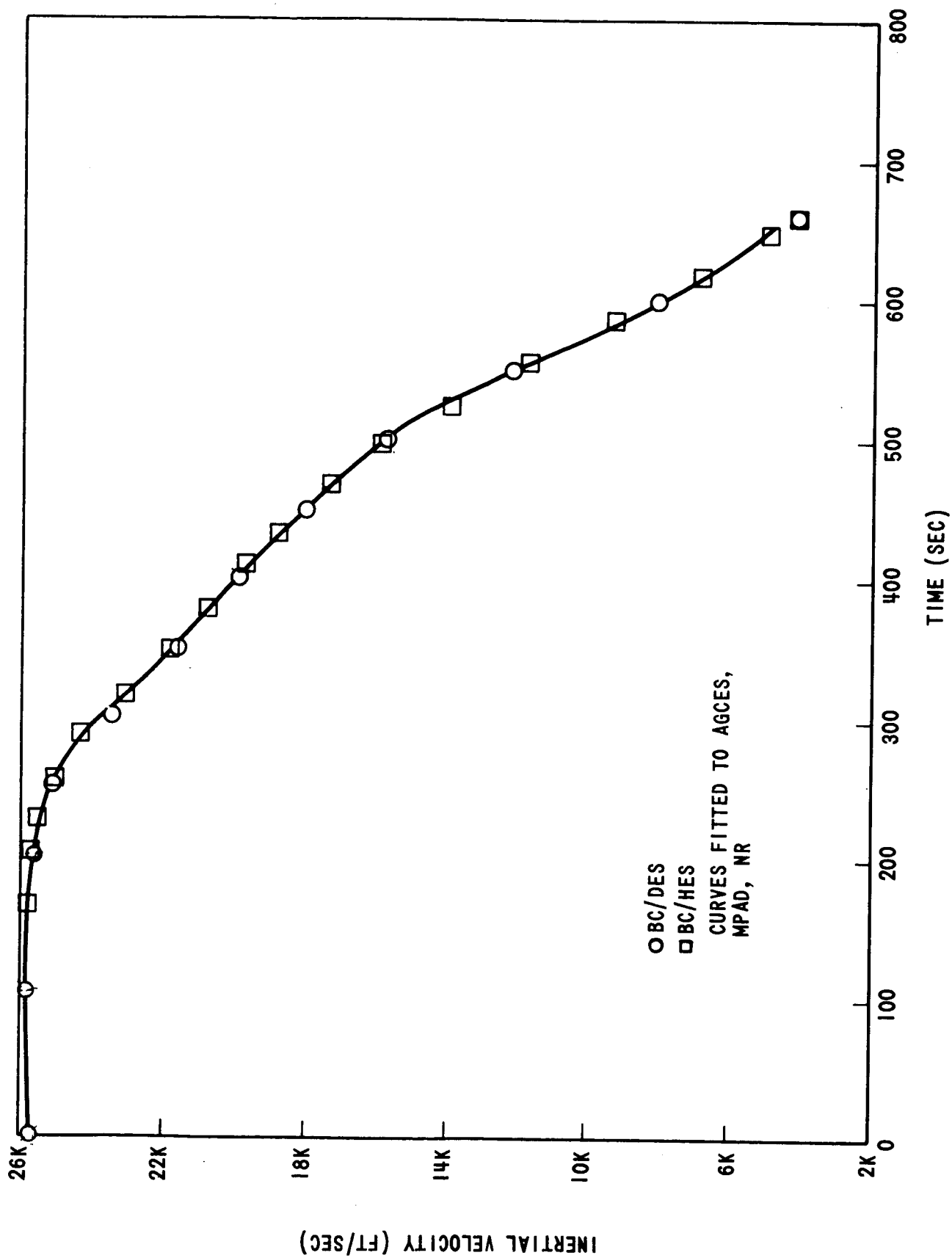


FIGURE 22 - INERTIAL VELOCITY vs. TIME - CASE 3 (LIFT UP)

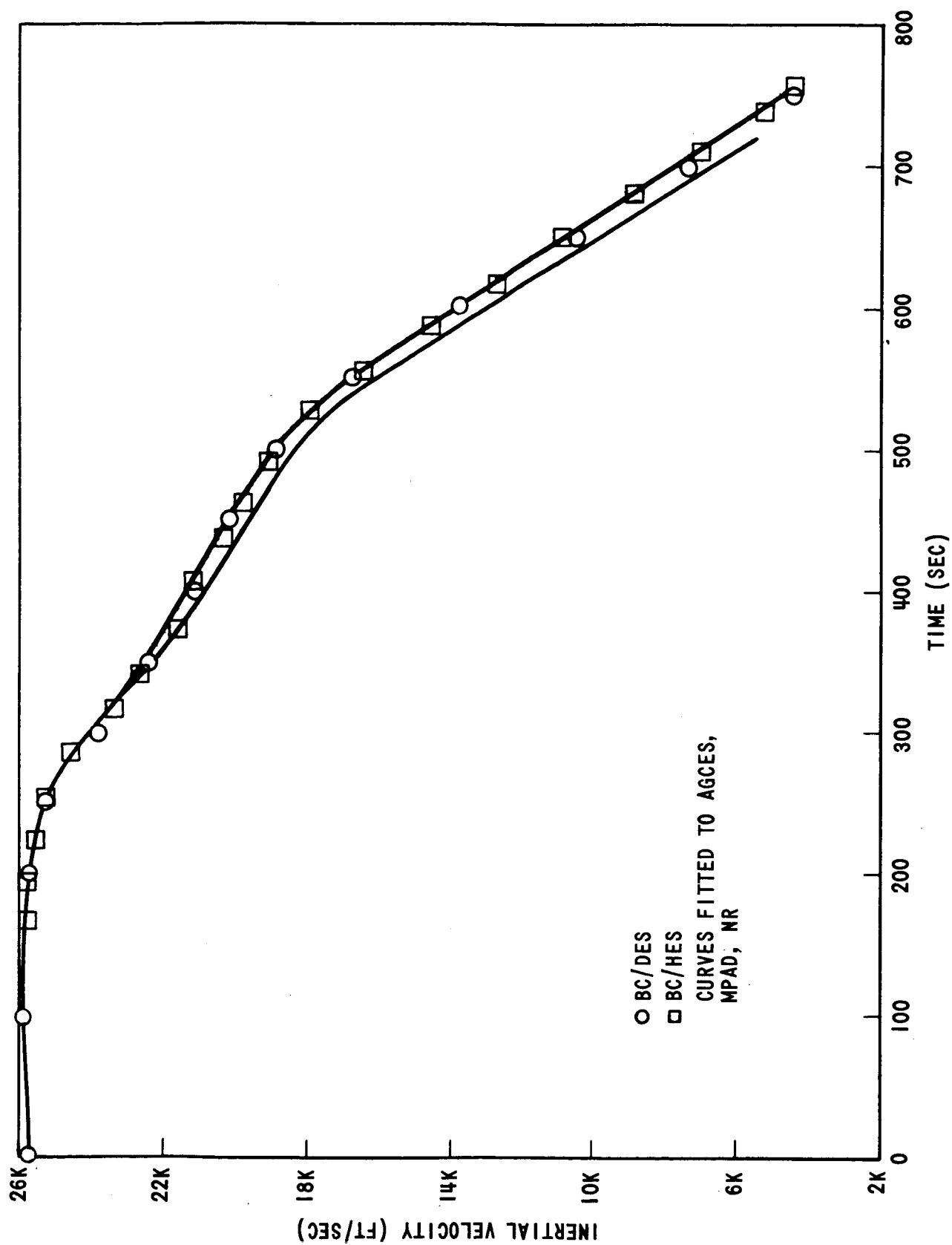


FIGURE 23 - INERTIAL VELOCITY vs. TIME - CASE 4 (LIFT UP)



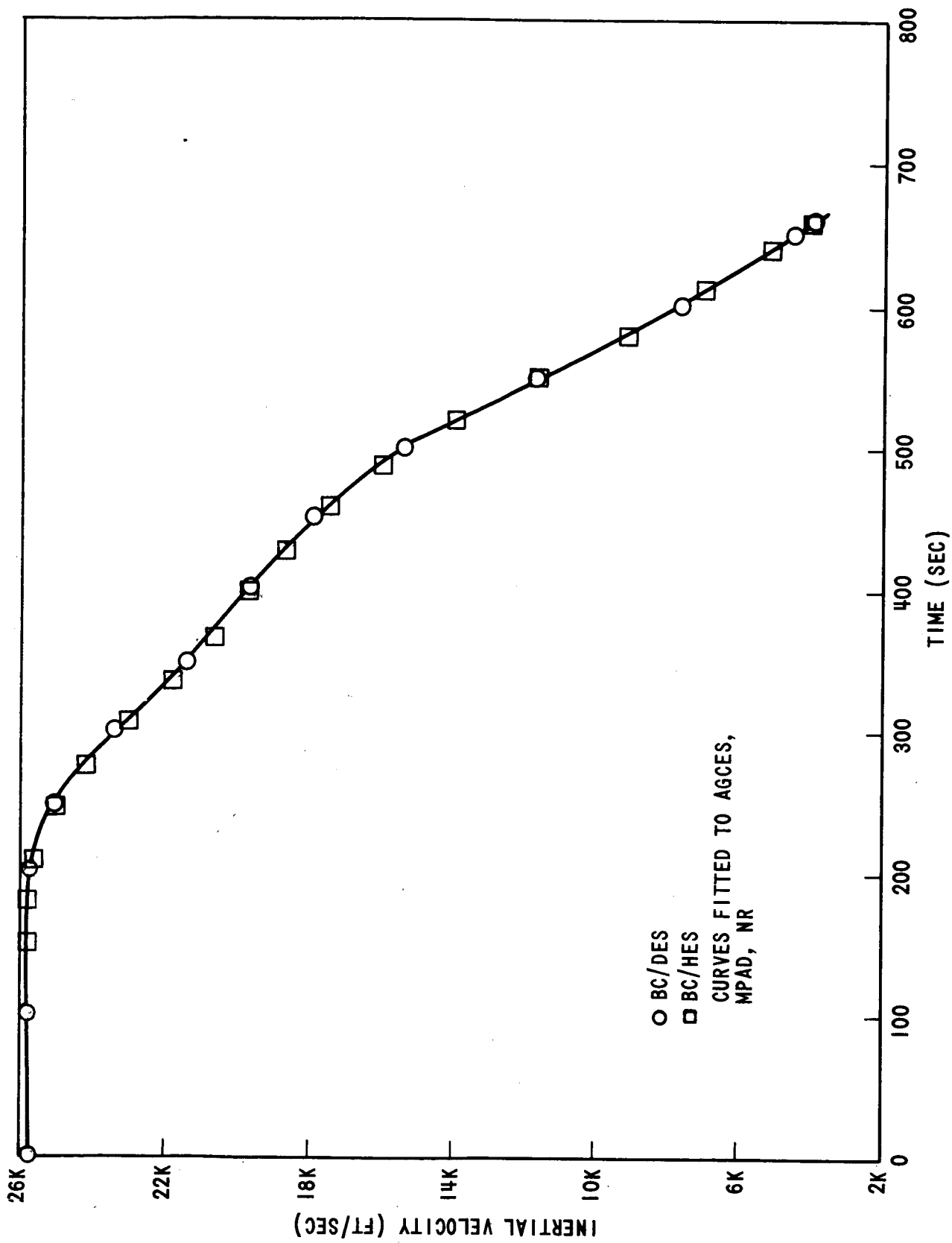


FIGURE 24 - INERTIAL VELOCITY vs. TIME - CASE 5 (LIFT UP)

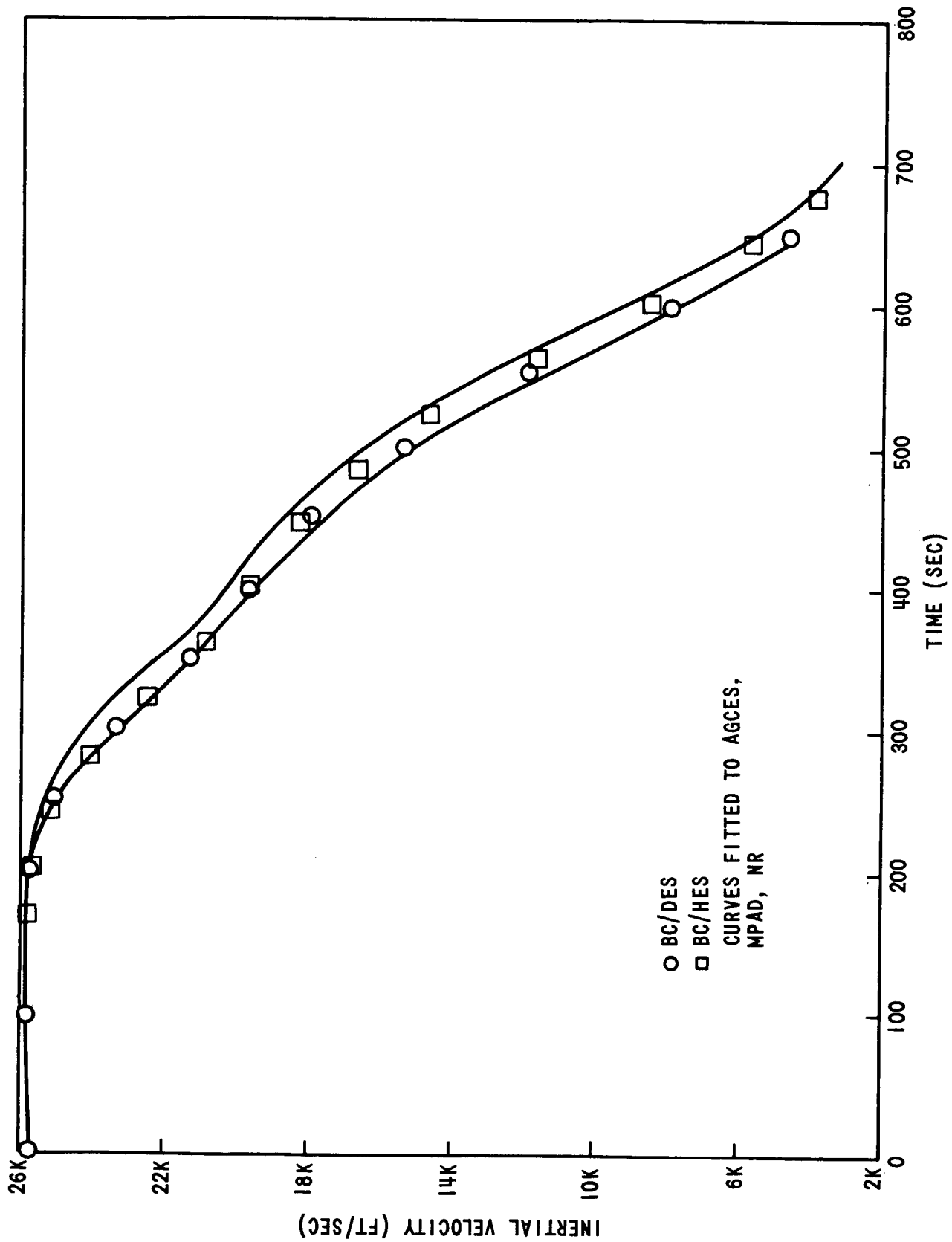


FIGURE 25 - INERTIAL VELOCITY vs. TIME - CASE 6 (LIFT UP)

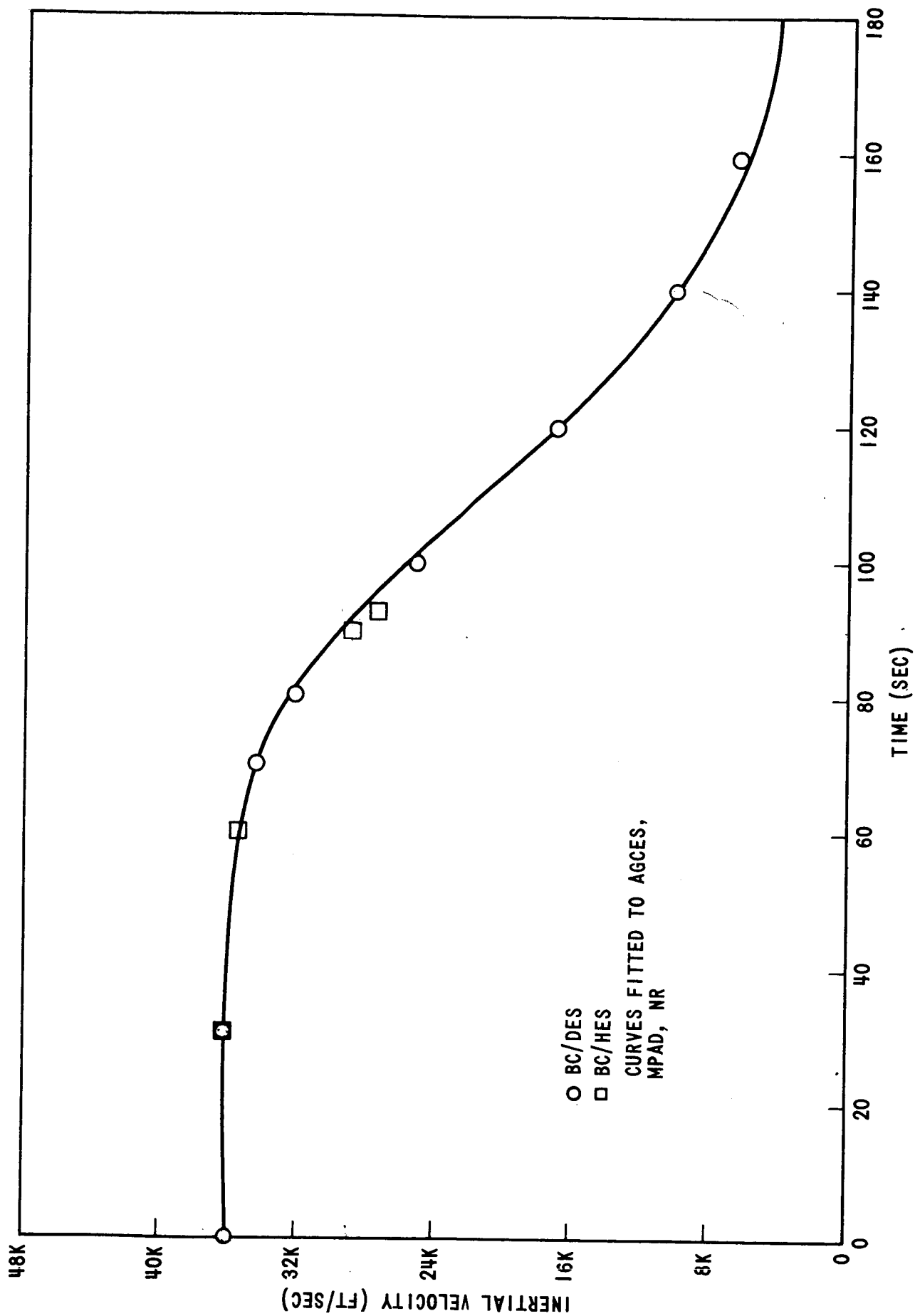


FIGURE 26 - INERTIAL VELOCITY vs. TIME - CASE 7 (ROLL 20°/SEC)